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## PRINCIPLES AND ALGORITHMS FOR NATURAL AND ENGINEERED SWARMS

P Krishnaprasad  
MARYLAND UNIV COLLEGE PARK

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Final Report

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## **Final Technical Report Submitted to AFOSR**

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### **Award Information:**

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**Abstract:** The PI (P. S. Krishnaprasad) and co-PI (Andrea Cavagna, sub-awardee at the ISC-CNR, Rome, Italy) joined forces in a program of experimental, theoretical and computational investigation to uncover the fundamental principles that govern collective phenomena in three dimensions (3D). The investigations considered phenomena at two ends of length scale: (a) Birds – flocking in a species of starling; and (b) Insects – swarming in a species of midge. A primary objective of this project was to uncover order and structure in such biological collectives, model the observed behavior, extract control laws at the individual level that govern collective behavior, and seek technological benefits (in applications to collective robotics) from this research. The experimental program led by Cavagna in Italy yielded new observations of starlings and midges in natural settings with higher temporal resolution than achieved before. (A prominent earlier experimental investigation supported by the European Union and also led by Andrea Cavagna had generated very interesting insights based on data obtained at coarse resolution.) The new data was analyzed by the Rome group via a series of computer vision based algorithms (segmentation, static matching, dynamic matching, static 3D-reconstruction, cluster analysis, stereo tracking – 3D reconstruction), **and** theoretical principles shaped by statistical physics. The theoretical program in Maryland yielded new results on certain key, network motifs (based on motion camouflage pursuit or parallel navigation, and constant bearing pursuit) to serve as fundamental building block models of complex collective behavior. The results in this direction include stability classification of dynamical interactions, extensions to 3D, symmetry reduction and phase portraits, top-down analysis based on configuration space methods, variational principles and robotic demonstrations. New control-theoretic algorithms for smoothing and curvature law extraction for trajectories were tested on starling data provided by the Co-PI. A number of archival publications in peer-reviewed high-impact journals, theses, and preprints as well as software have been created as a result of this project. Further analyses and development of archival publications continue.

**Materials and Methods:** There are two different traditions of intellectual inquiry that have guided the progress made in this project. The co-PI Andrea Cavagna, as a physicist rooted in

condensed matter theory came to the problem of collective behavior from a statistical mechanics perspective. Further he and his team developed from the ground up a strong set of skills in visual observations using carefully synchronized camera networks to resolve large flocks of birds as they moved in the skies over Rome to obtain useful quantitative information on trajectories. The associated methods (and results) are described in detail in the **Section beginning on page 10** about **Experimental Data Gathering and Theoretical Analysis**. The approach adopted in the efforts at Maryland is strongly shaped by the advances in nonlinear and geometric control theory in which the PI has made significant prior contributions. Since the beginning of 2000 these methods were introduced into the subject of collective behavior by the PI, with support from AFOSR, ARO and ONR. During the course of this AFOSR project (2010 – 2014) significant new conceptual advances were made by taking a geometric approach to the analysis and synthesis of collective behavior. **First**, the self-steering particle model of an agent in a collective, introduced in earlier work by the PI, proved to be a strong basis for further developments. This class of models has in its core the notion of gyroscopically interacting systems (i.e. particles subject to forces orthogonal to velocities), in contrast with literature rooted in the many-body problems of celestial mechanics. We note that, the study of collective behavior has a distinguished role in the foundations of physical science, as in work on the problem of stability of the solar system (by Lagrange, Laplace and their illustrious descendants), and James Clerk Maxwell's investigation of the character and stability of Saturn's rings (1859). But collective behavior as observed in biological organisms (birds, insects, fish, dolphins etc.) mediated by sensory modalities such as vision, bio-sonar and olfaction is *more naturally* modeled by steering laws (i.e. laws that change direction of movement) under the influence of such sensory feedback, in contrast to using forces of attraction and repulsion as encountered say in celestial mechanics and chemistry. This outlook led us to the idea of creating and studying collective behavior out of dyadic building-block interactions (such as motion camouflage (MC), constant bearing pursuit (CB), boundary following (BF), etc.).

As a result of the focus on gyroscopic interactions, a **second** distinctive feature of this project is that geometric ideas occupy a central place in our conceptual framework. Geometry enters the investigation of collective behavior from multiple vantage points: the structure of configuration space; the synthesis of control strategies; the role of symmetries and reduction in closed loop dynamics; the analysis of empirical data from biology; and the realization of control strategies in autonomous systems. In particular, the geometry of the Euclidean group in 2 and 3 dimensions and its role in formulating models via theory of moving frames is of central interest. Methods from graph theory were used to assemble such dyadic interactions into collective behavior e.g. constant bearing cyclic pursuit.

**Third**, we made progress in the project in these afore-mentioned directions, by benefiting from close study of low dimensional examples. Building on experience with data from prey-capture experiments involving echolocating bats, we developed methods to assimilate sampled observations of collectives of continuous time dynamical systems, e.g. predator-prey encounters and bird (starlings) flocking events, into generative models with continuous time inputs and outputs. Results of such assimilation (reconstruction) were used to evaluate hypotheses of interest, based on correlations, delays, and possible mechanisms of interaction between elementary units of the observed population. Using models based on moving frames and methods from nonlinear smoothing, we found ways to solve the problem of numerically reconstructing

collectives. We also made effective use of optimal control methods for computational schemes, and formulation of optimality principles for collective behavior. We further tested our ideas and algorithms in a physical system test-bed based on motion capture cameras and mobile robots acquired and installed in the Intelligent Servosystems Laboratory, thanks to a DURIP award through AFOSR. Software tools developed in Maryland for data analysis have been tested on a variety of flocking events.

**Illustrative descriptions of the work done under the project:** Key outcomes of the project are best captured by the descriptions of two Ph.D. dissertations and a Ph.D. research proposal on a dissertation to be defended in February 2015.

(i) Ph. D. Dissertation of K. S. Galloway (2011) – **Cyclic Pursuit: Symmetry, Reduction and Nonlinear Dynamics**. In this dissertation, we explore the use of pursuit interactions as a building block for collective behavior, primarily in the context of constant bearing (CB) cyclic pursuit. Pursuit phenomena are observed throughout the natural environment and also play an important role in technological contexts, such as missile-aircraft encounters and interactions between unmanned vehicles. While pursuit is typically regarded as adversarial, we demonstrate that pursuit interactions within a cyclic pursuit framework give rise to seemingly coordinated group maneuvers. We model a system of agents (e.g. birds, vehicles) as particles tracing out curves in the plane, and illustrate reduction to the shape space of relative positions and velocities. Introducing the CB pursuit strategy and associated pursuit law, we consider the case for which agent pursues one other agent using a CB pursuit law. After deriving closed-loop cyclic pursuit dynamics, we demonstrate asymptotic convergence to an invariant submanifold (corresponding to each agent attaining the CB pursuit strategy), and proceed by analysis of the reduced dynamics restricted to the submanifold. For the general setting, we derive existence conditions for relative equilibria (circling and rectilinear) as well as for system trajectories which preserve the shape of the collective (up to similarity), which we refer to as pure shape equilibria. For two illustrative low-dimensional cases, we provide a more comprehensive analysis, deriving explicit trajectory solutions for the two-particle cyclic case, and detailing the stability properties of three-particle relative equilibria and pure shape equilibria. For the three-particle case, we show that a particular choice of CB pursuit parameters gives rise to remarkable almost-periodic trajectories in the physical space. We also extend our study to consider CB pursuit in three dimensions, deriving a feedback law for executing the CB pursuit strategy, and providing a detailed analysis of the two-particle mutual pursuit case. We complete the work by considering evasive strategies to counter the motion camouflage (MC) pursuit law. After demonstrating that a stochastically steering evader is unable to thwart the MC pursuit strategy, we propose a (deterministic) feedback law for the evader and demonstrate the existence of circling equilibria for the closed-loop pursuer-evader dynamics.

(ii) Ph.D. dissertation of M. Mischiati (2011) – **Analysis and Synthesis of Collective Motion: from Geometry to Dynamics**. The subject of this dissertation is collective motion, the coordinated motion of two or more individuals, in three-dimensional space. Inspired by the problems of understanding collective motion in nature and designing artificial collectives that can produce complex behaviors we introduce mathematical methods for the analysis of collective motion data, and biologically-inspired algorithms for generating collective motion in engineered systems. We explore two complementary approaches to the analysis and synthesis of collective

motion. The first "top-down" approach consists in exploiting the geometry of  $n$ -body systems to identify certain elementary components of collective motion. A main contribution of this thesis is to reveal a new geometrical structure (fiber bundle) of the translation-reduced configuration space and a corresponding classification of collective motions alternative to the classical one based on reduction to shape space. We derive a mathematical framework for decomposing arbitrary collective motions into elementary components, which can help identify the main modes of an observed collective phenomenon. We synthesize vector fields that implement some of the most interesting elementary collective motions, and suggest, whenever feasible, decentralized implementations. The second "bottom-up" approach consists in starting from known biologically-plausible individual control laws and exploring how they can be used to generate collective behaviors. This approach is illustrated using the motion camouflage proportional guidance law as a building block. We show that rich and coordinated motion patterns can be obtained when two individuals are engaged in mutual pursuit with this control law. An extension of these dynamics yields coordinated motion for a collective of  $n$  individuals.

(iii) Ph.D. dissertation proposal of B. Dey (2013) – **Reconstruction, Analysis and Synthesis of Collective Motion.** As collective motion plays a crucial role in modern day robotics and engineering it seems appealing to seek inspiration from nature, which abounds with examples of collective motion (starling flocks, fish schools etc.). This approach towards understanding and reverse-engineering a particular aspect of the nature forms the foundation of this research proposal, and the main contribution of this proposal is threefold. First we identify the importance of appropriate algorithms to extract parameters of motion from sampled observations of the trajectory, and then by assuming a proper generative model we turn this into a regularized inversion problem with the regularization term imposing smoothness of the reconstructed trajectory. First we assume a linear triple integrator model, and by penalizing high values of the jerk path integral we reconstruct the trajectory through an analytical approach. Alternatively, the evolution of a trajectory can be governed by natural Frenet frame equations. Inadequacy of integrability theory for nonlinear systems poses the utmost challenge in having an analytic solution, and forces us to adopt a numerical optimization approach. However by noting the fact that the underlying dynamics defines a left invariant vector field on the Lie group, we develop the initial framework (based on Pontryagin's maximum principle) to obtain a semi-analytic solution in this case. Equipped with the appropriate algorithms for trajectory reconstruction we analyze flight data for biological motions, and this marks the second contribution of this proposal. By analyzing the trajectory data of bat flight in two different settings (chasing a free flying praying mantis and competing with a conspecific to catch a tethered mealworm) we provide evidence to show the presence of a context specific switch in flight strategy. Moreover, our approach provides a way to estimate the behavioral latency associated with these flights. On the other hand, we have also analyzed the trajectory data for flocking events by European starlings, and it can be concluded from our data that the flock-averaged coherence (the average cosine of the angle between the velocities of a focal bird and its neighborhood center of mass, averaged over the entire flock) gets maximized by considering 5-7 nearest neighbors. Therefore, according to our data, topological notion of distance plays a more important role than the metrical notion. The third and final contribution of this proposal lies in the domain of control law synthesis. Drawing inspiration from coherent movement of starling flocks, we introduce a strategy (Topological Velocity Alignment) for collective motion, wherein each agent aligns its velocity along the direction of motion of its neighborhood center of mass. A feedback law has

also been proposed for achieving this strategy, and we have analyzed two special cases (two-body system; and an N-body system with cyclic interaction) to show effectiveness of our proposed feedback law. It has been observed through numerical simulation that this approach towards collective motion can give rise to a splitting behavior.

**Significance of the work supported by the AFOSR grant:** The work has led to advancing our understanding of collective behavior through fundamental building-block interactions captured by biologically plausible feedback laws. It has also provided guidance on exploiting these advances by implementation of such feedback laws in robot collectives in a physical system test-bed at the University of Maryland. It has advanced the technology of data gathering on collective behavior and related statistical physics based theoretical analysis, as an outcome of the work by the collaborators of ISC-CNR in Rome, led by the co-PI.

**Students trained because of funding from the AFOSR grant:** Kevin S. Galloway (PhD 2011), Matteo Mischiati (PhD 2011) received partial support during their studies from this grant. Biswadip Dey (PhD expected 2015) was fully supported by this grant.

**Recognition** P. S. Krishnaprasad received the Baetjer Colloquium Lectureship for 2012 from the Mechanical and Aerospace Engineering Department of Princeton University, *in recognition of contributions to the field of geometric control, filtering theory, robotics & bio-inspired design* - lecture delivered on “Structure and Dynamics in Collectives” (April 20, 2012), acknowledged AFOSR support.

#### **Archival Publications (of PI – P. S. Krishnaprasad):**

C. Chiu, P. V. Reddy, W. Xian, P. S. Krishnaprasad, and Cynthia F. Moss. “Effects of competitive prey capture on flight behavior and sonar beam pattern in paired big brown bats, *Eptesicus fuscus*,” *The Journal of Experimental Biology*, 2010, Vol. 213, Issue 19, 3348-3356.

E. W. Justh and P. S. Krishnaprasad. “Optimal Natural Frames,” *Communications in Information and Systems*, 2011, Vol. 11, No. 1, pp. 17-34 (published online October 2010).

Matteo Mischiati and P. S. Krishnaprasad. “Motion Camouflage for Coverage,” *Proceedings of the American Control Conference*, 2010, 6429-6435, American Automatic Control Council, Philadelphia.

K. S. Galloway, E. W. Justh and P. S. Krishnaprasad. “Cyclic Pursuit in Three Dimensions,” *Proceedings of the 49th IEEE Conference on Decision and Control*, 2010, 7141-7146, IEEE, New York.

E. W. Justh and P. S. Krishnaprasad. “Extremal Collective Behavior,” *Proceedings of the 49th IEEE Conference on Decision and Control*, 2010, 5432-5437, IEEE, New York.

M. Mischiati and P. S. Krishnaprasad. “Mutual Motion Camouflage in 3D,” *Proceedings of the 18<sup>th</sup> World Congress of the International Federation of Automatic Control*, 2011, pp. 4483-4488.

K. S. Galloway, E. W. Justh and P. S. Krishnaprasad. "Portraits of Cyclic Pursuit," *Proceedings of the 50<sup>th</sup> IEEE Conference on Decision and Control and European Control Conference (CDC-ECC)*, 2011, pp. 2724-2731, IEEE, New York.

M. Mischiati and P. S. Krishnaprasad. "Dynamics of Mutual Motion Camouflage," *Systems and Control Letters*, 2012, 61(9), pp. 894-903.

B. Dey and P. S. Krishnaprasad. "Trajectory Smoothing as a Linear Optimal Control Problem," *Proceedings of the 50<sup>th</sup> Allerton Conference on Communication, Control and Computing*, 2012, pp. 1490-1497, ieeexplore, <http://dx.doi.org/10.1109/Allerton.2012.6483395>

Fumin Zhang, Eric W. Justh, and P. S. Krishnaprasad. "Boundary Tracking and Obstacle Avoidance using Gyroscopic Control," (eds. A. Johann, H-P. Kruse, F. Rupp, and S. Schmitz), pp. 417-446, *Recent Trends in Dynamical Systems, Proceedings of Conference in honor of Juergen Scheurle*, Springer Proceedings in Mathematics & Statistics, vol. 35 Basel, Switzerland: Springer, 2013.

K. S. Galloway, E. W. Justh and P. S. Krishnaprasad. "Symmetry and reduction in collectives: cyclic pursuit strategies" (2013), *Proceedings of the Royal Society of London A*, **469**, 20130264, online 21 August 2013, 24 pages + 12 pages supplement, <http://dx.doi.org/10.1098/rspa.2013.0264>

B. Dey and P. S. Krishnaprasad. "Control-theoretic Data Smoothing," in press, *Proceedings of 53<sup>rd</sup> IEEE Conference on Decision and Control*, December 2014, 7 pages, IEEE, New York

E. W. Justh and P. S. Krishnaprasad. "Optimality, Reduction and Collective Motion," submitted for publication, 2014, 21 pages main text + 20 pages electronic supplement. (status – under peer review).

#### **Other related publications from PI's group:**

K. S. Galloway and B. Dey. "Station-keeping through Beacon-referenced Cyclic Pursuit," 2014, submitted for publication (status – under peer review).

U. Halder and B. Dey. "Biomimetic Algorithms for Coordinated Motion: Theory and Implementation," 2014, submitted for publication (status – under peer review).

#### **Doctoral Dissertations directed by PI**

Kevin S. Galloway (2011). *Cyclic Pursuit: Symmetry, Reduction and Nonlinear Dynamics*, Ph. D. Thesis, Department of Electrical and Computer Engineering, University of Maryland, College Park, MD. <http://hdl.handle.net/1903/12226> Galloway completed a post-doctoral fellowship from 2011 till 2013 at the University of Michigan, Ann Arbor, working on bi-pedal locomotion; since 2013 he has been on the faculty of the Electrical and Computer Engineering Department, United States Naval Academy (USNA) as an Assistant Professor (active duty with the rank of Commander), and will start in fall 2015 a tenure track Assistant Professorship at USNA. He is



also continuing as a visiting researcher at the Intelligent Servosystems Laboratory of the University of Maryland, collaborating with the PI and his graduate students.

Matteo Mischiati (2011). *Analysis and Synthesis of Collective Motion: from geometry to dynamics*, Ph. D. Thesis, Department of Electrical and Computer Engineering, University of Maryland, College Park, MD. <http://hdl.handle.net/1903/12250> Since 2011 Mischiati has held a post-doctoral researcher position in the Laboratory of Dr. Anthony Leonardo of Janelia Farm Research Campus, HHMI. He is conducting research in the flight behavior of dragonflies engaged in prey capture using variety of methods to study fundamental questions, including flight trajectory tracking using high-precision motion capture, modeling, and control-theoretic analysis. Some of the results of this work are appearing in a high-impact journal (*Nature*) on December 11, 2014.

### **Doctoral Dissertation Research in progress directed by PI**

Biswadip Dey – *Reconstruction, Analysis and Synthesis of Collective Motion* – dissertation research **proposal** accepted in fall 2013, expected date of completion of dissertation, February 2015, Department of Electrical and Computer Engineering, University of Maryland, College Park, MD.

### **Involvement of Undergraduate Students in the Project**

Two students Benjamin Flom (B.S. in Mathematics and B.S. in Electrical Engineering) and Garrett Wenger (B.S. in Electrical Engineering) have participated in various aspects of the project including exploration of directions such as data analysis of pigeon flocks (from data available in a Nature public repository) and predator avoidance. After a brief period at a software startup, Flom is pursuing chip design work in industry in Israel. Wenger is pursuing Ph.D. studies at the University of Pennsylvania.

### **Invited Lectures Delivered by PI**

Army Research Laboratory, Aberdeen: (August 4, 2011) “Strategies for Autonomy and Cohesion”.

Applied Dynamics and Geometric Mechanics Meeting, Mathematisches Forschungsinstitut Oberwolfach, Germany: (August 15, 2011) “Control of Collectives”.

Intelligent Automation - ISR Colloquium, Maryland: (December 7, 2011) “Reconstructing Collectives”

The Edwin Baetjer Distinguished Colloquium Lecture, Princeton University: (April 20, 2012) “Structure and Dynamics in Collectives”

Workshop on Dynamics of Prey Capture and Escape, Janelia Farm Research Campus of HHMI: (March 7, 2013) “Latency and Stochasticity”

Summer School on Geometry, Mechanics and Control ICMAT VII, Madrid, Spain: (July 1- July 5, 2013) – 6.5 hours lecture series - “Geometry of Collectives: Control, Dynamics and Reconstruction”

AFOSR Sensory Information Systems Program Review, REEF Center, Shalimar, Florida: (Oct 21-25, 2013) “Geometry of Collectives: Control, Dynamics and Reconstruction”

Workshop - Perspectives in Dynamical Systems & Control (VJTI and IIT Bombay, TEQIP-II) Indian Institute of Technology, Bombay, INDIA (March 17-22, 2014) – two talks delivered over the web, each lasting about 1.5 hours.

Lecture 1 “Geometry of Collectives: Control, Dynamics and Reconstruction”

Lecture 2 “Optimality in Collectives”

George Washington University, MAE Seminar, Washington D.C. : (May 22, 2014) “Geometry of Collectives: Control, Dynamics, and Reconstruction”

AFOSR Sensory Information Systems Program Review, Doolittle Institute, Shalimar, Florida: (Oct 6 - 8, 2014) “Optimality in Collectives: Seeking Hamilton(ian)”

Workshop - Swarms with a Purpose: Collective Motion, Dynamics and Control: From Bacteria to Ballet, Radcliffe Institute for Advanced Study, Harvard University, Cambridge, MA (December 11-12, 2014) “Optimality in Collectives: seeking Hamiltonian”

Workshop (all-day) at 53<sup>rd</sup> IEEE Conference on Decision and Control, Los Angeles, CA: (December 14, 2014) “Geometry of Collectives: Control, Dynamics, and Reconstruction” – PI will speak on *Dyadic Building-block Interactions: Pursuit, Escape and Other*. There are five other 1 hour talks as part of the workshop, all connected to research outcomes supported by the AFOSR grant.

### **Archival Publications (of Co-PI – A. Cavagna):**

A. Procaccini, A. Orlandi, A. Cavagna, I. Giardina, F. Zoratto, D. Santucci, F. Chiarotti, C. K. Hemelrijk, E. Allea, G. Parisi, and C. Carere. “Propagating waves in starling, *Sturnus vulgaris*, flocks under predation. *Animal Behaviour*, 2011, **82**, 759–765.

W. Bialek, A. Cavagna, I. Giardina, T. Mora, E. Silvestri, M. Viale, A. Walczak. “Statistical Mechanics of Natural Flocks of Birds,” *Proceedings of the National Academy of Sciences*, 2012, Vol. 109, 4786

G. F. Young, L. Scardovi, A. Cavagna, I. Giardina, N. E. Leonard,. “Starling Flock Networks Manage Uncertainty in Consensus at Low Cost,” *PLOS Computational Biology*, 2013, Vol. 9, No. 1, e1002894

M. Camperi, A. Cavagna, I. Giardina, G. Parisi, E. Silvestri. “Spatially Balanced Topological Interaction Grants Optimal Cohesion in Flocking Models,” *Interface Focus*, 2012, <http://dx.doi.org/10.1098/rsfs.2012.0026>

A. Cavagna, S. M. Duarte Queiros, I. Giardina, F. Stefanini and M. Viale. “Diffusion of Individual Birds in starling flocks,” ArXiv: 1206443, published in February 2013 in *Proc. Royal. Soc. B*, 280, 1756.

A. Cavagna, I. Giardina, F. Ginelli. “Boundary information inflow enhances correlation in flocking,” ArXiv: 0502936, *Physical Review Letters*, 2013, Vol. 110, 168107.

A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, S. Melillo, L. Parisi, O. Pohl, B. Russaro, E. Shen, E. Silvestri, M. Viale. “Finite-Size Scaling as a Way to Probe Near-Criticality on Natural Swarms,” *Physical Review Letters* **113**, 238102 (2014).

A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, T.S. Grigera, A. Jelic, S. Melillo, L. Parisi, O. Pohl, E Shen, and M. Viale. “Information Transfer and Behavioural Inertia in Starling Flocks,” *Nature Physics*, 2014, Vol. 10, 691-696

A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, A. Jelic, S. Melillo, L. Parisi, E. Shen, E. Silvestri, M. Viale, *Tracking in three dimensions via multi-path branching*. arXiv:1305.1495 [q-bio.QM] (2013). Manuscript submitted to Transaction of Pattern Analysis and Machine Intelligence.

**Report on the program of Experimental Data Gathering and Theoretical Analysis conducted under the leadership of the Co-PI Andrea Cavagna in Rome (sub-awardee of University of Maryland)**

**Section 1 - Accomplishments during the first year of performance (2010-2011) of the group of Co-PI Cavagna in Rome.**

During the **first year of performance** (2010-2011) the experimental program in Italy yielded new observations of starlings and midges in natural settings with higher temporal resolution than achieved before. The data was subject to a series of computer vision based analyses (segmentation, static matching, dynamic matching, static 3D-reconstruction, cluster analysis, stereo tracking – 3D reconstruction).

**High Speed Camera Verification Testing**

Three high speed cameras are required for data acquisition of collective behavior. The camera selected for this purpose is the IDT M5, which has a maximum frame rate of 170 frames per second (fps) at a resolution of 2288x1728. Verification tests were conducted on this camera prior to purchase. These tests included: pixel sensitivity, noise characterization, image saving time, multiple camera synchronization and frame rate verification. The last two tests were conducted using an in-house custom designed target consisting of a 360° protractor and disk with needle connected to a high speed stepper motor. The period of revolution was calibrated and verified using an optical counter.

**Calibration Methods**

For the earlier European union funded Starflag project, the camera/lens combination was calibrated by a third-party company. In the AFOSR-funded project through the University of Maryland, all camera calibrations (intrinsic and extrinsic parameters) are carried out in-house.

*Intrinsic Parameters*

Taking inspiration from the calibration methods used by the Bodenschatz Turbulence Group at the Max Planck Institute, the following camera intrinsic parameters are of interest: the focal length ( $\Omega$ ), the principal point ( $u_o, v_o$ ) and the 1<sup>st</sup> radial distortion parameter ( $k_1$ ). Limiting the number of intrinsic parameters reduces the errors produced during the optimization stage of the calibration methodology.

The core camera calibration function is provided by the Open Computer Vision (OpenCV) library, which is the translation of the Camera Calibration Toolbox for MATLAB into C/C++. The target for the calibration is a 2D black and white checkerboard pattern. In a typical set of calibration images subsequent images tend to be related to one another by a rotation, tilt or translation. It is then possible to introduce bias if a block of consecutive images are used. Hence a new method for determining the intrinsic parameters we developed to reduce target orientation bias, known as the iterative median method. In this method, a set of  $M$  trials are conducted each with an increasing number of iterations ( $N_M$ ). Each iteration returns a set of intrinsic parameters based on  $P$  randomly selected images from the total set of images ( $T$ ) of the calibration target in different orientations. The first trial ( $M = 1$ ) is initialized using the theoretical values of the intrinsic parameters – manufacturer's focal length in pixels, principal point at the center of the image and zero distortion. Each subsequent trial ( $M > 1$ ) is initialized using the median value of the  $N_M$  intrinsic parameters calculated from the previous trial. A typical set of values used in the iterative median method are:  $M = 5$ ,  $N_M = (10, 20, 50, 100, 1000)$ ,  $P = 20$  and  $T = 50$ .

*Extrinsic Parameters*

The method for determining the extrinsic parameters (i.e. the mutual Euler angles and translation vectors between the 3 cameras) differs for the two different collective groups that are under investigation. For the starling flocks, the method is identical to that of the original Starflag project – a wire and various gauges are used to align Cameras 2 and 3 to known relative angles while the position and orientation of Camera 1 are unknown (only required to aid in stereo matching). When photographing midge swarms, it is not possible to wait in a given location for a swarming event to enter the cameras' overlapping fields-of-view. Hence the alignment of the cameras using the wire method is not possible. We developed a new method using two targets separated by a known distance and zero temperature Monte Carlo optimization. This calibration method is further described in the Data Acquisition – Midge Swarms section.

## **Data Acquisition – Starling Flocks**

### *Summary of Experimental Procedure*

Experiments are carried out on the roof of Palazzo Massimo alle Terme overlooking the bus transit center of Termini station. Cameras 1 and 2 are located on the right side of the roof (when looking at Termini station), approximately 3 m apart, while Camera 3 is 25 m to the left of Camera 2. The cameras were set at 80 fps as a compromise between temporal resolution and total length of event captured (the cameras are limited to a maximum of 2500 images per acquisition regardless of frame rate). The three cameras are setup such that the fields-of-view overlap approximately 100 m from the cameras. The cameras are set in pre-trigger mode, meaning that the cameras continuously buffer images until the trigger is depressed whereby the buffer is saved to hard disk. This means the flocking behavior can be “previewed” prior to saving, thus increasing the probability of capturing desirable events.

### *Experimental Issues Resolved*

While conducting an infinity test (shooting targets at a distance much larger than the stereo baseline) to determine the angle correction factor (a parameter to correct for any angular offset between the camera sensor and the camera body) it was determined that the original mounting blocks for the IDT cameras were not wide enough to prevent small rotations when mounted on the rigid camera bar. After constructing wider mounting blocks, the cameras could be mounted with more predictability. A second issue resolved improved image sharpness. Originally, when the lens (Schneider 28mm) was used at low f# the images were severely blurred, especially in the corners. After several different focusing tests, it was discovered that the lens mounting flanges on the cameras were not set at the proper distance from the image sensor. After adjusting the flange on each camera, the image quality at low f# improved drastically.

### *Experimental Results*

The starling season begins approximately at the beginning of December and lasts till near the end of February. During the past season 122 starling flocking events were captured. 94 of these were captured prior to the flange adjustment. Although these acquisitions are not of the highest image quality, they are still usable, particularly for testing image processing algorithms. Of the 122, 45 of these events are considered high quality in terms of segmentation potential and flock isolation (only a single flock in the field-of-view).

## **Data Acquisition – Midge Swarms**

### *Summary of Experimental Procedure*

The experimental setup for capturing midge swarms is more compact than for starling flocks. Cameras 1 and 2 are mounted on the same camera bar, approximately 25 cm apart. Camera 3 is mounted on a separate bar. The separation distance between Camera 2 and 3 is governed by the distance from the cameras to the swarm based on an estimate of the acceptable magnitude of inter-midge distance error. A typical set up has Camera 2 and 3 about 8 m from the swarm and Camera 3 about 4 m to the left of Camera 2 (when looking from behind Camera 2). Since midge swarm movements are more erratic and have higher velocities, the cameras are set at the highest frame rate of 170 fps. The cameras are set to post-trigger mode – images are captured after the trigger button is depressed. The reason for this setting is described below.

### *Experimental Issues Resolved*

In a typical acquisition session, two operators track the swarm using the micrometric tripod heads until the swarm stabilizes at a fixed location. Only at that point is a sequence of images captured. This precludes the use of the alignment wire as the final position of the cameras is a function of the location of the swarm. To determine the extrinsic parameters of the cameras, a new extrinsic calibration technique was developed. The calibration rig (shown in Figure 1) consists of two targets mounted on a rigid bar, each consisting of two white and two black solid rectangles in a checkerboard pattern. This pattern forms two perpendicular lines that cross at a point (target center). To identify the two targets, the targets have been made such that they are mirror images of one another. The distance between the target centers ( $\Delta r$ ) can be precisely measured using a laser to within  $\pm 0.002$  m. A set of 25 images of the calibration rig in various orientations are taken in the field once swarming activity has ended. The target center image locations are extracted, with sub-pixel accuracy of 0.25 pixels, using custom software that requires the user to manually click nearby the target centers. The target center image points for two cameras are then used to calculate the essential matrix of the two cameras (assumption is that intrinsic parameters of each camera are available) using a linear set of equations and singular value decomposition (SVD). The essential matrix can then be decomposed into rotation and translation matrices (extrinsic parameters) that relate the position of one camera with respect to the camera center of the other. The assumption here is that the world reference frame is located at the camera center of one camera. The final purpose of the extrinsic parameters is to reconstruct the 3D location of individual midges and of particular interest is precisely determining the inter-midge distances. To reduce the error in the calculation of inter-midge distances, the final step of the extrinsic parameter calibration optimizes the rotation and translation parameters by minimizing the distance error between the target center points. This optimization is carried out using a zero temperature Monte Carlo algorithm. Figure 2 illustrates the typical distance error between target centers ( $\delta(\Delta r)$ ) for a set of 25 images with a inter-target separation of  $\Delta r = 1$  m. Note that the largest absolute error is 0.002 m with the average error being approximately 0.0007 m.

### *Experimental Results*

An initial set of 19 image sequences have been captured with 14 of these sequences being of high quality (reasonable backgrounds leading to a higher probability of proper image segmentation). All these sequences were captured at Villa Paganini.

### *Current State of Experiment*

Data acquisition is in progress. The anticipated length of the midge swarming season is from the beginning of May until the end of October or the middle of November (depending on the weather). A current experimental issue to be resolved is selecting a preferred location, which offers an acceptable background (no regions of image saturation and little or no movement), enough room for experimental equipment, proper light conditions (swarms tend to occur at the interface between sunlight and shadow)

and reasonable swarm size (has to fit within the field-of-view of a camera) and density (increasing density reduces image segmentation efficacy). Villa Paganini is a strong candidate since the majority of these conditions are met. However, lighting has become an issue. A possible solution to this problem is to use a landmark to move/attract midge swarms to a favorable location. Experiments to determine the correct landmark and the effectiveness of the landmarks are ongoing, but initial tests have shown that it is possible to attract and also move a swarm to a more desirable location.

## **Computer Vision Accomplishments**

Due to the acquisition of new high speed cameras, the sequence of digital stereoscopic images of an animal group (flock and/or swarm) taken in the new project are much longer temporally with each image being of lower resolution, compared to the StarFlag project. The consequence of having higher temporal resolution is that the computer vision analysis requires higher processing specifications. Also, image segmentation of lower resolution images becomes more difficult.

To cope with these two issues, we developed a new software framework, using the paradigm of full integration that can process all images simultaneously. This is in contrast to the software architecture employed in the StarFlag project, which analyzed each image separately. The new framework increases the flexibility of processing algorithms that can be implemented as simultaneous frame analysis allows feedback strategies to be added along with statistical information to be collected. The latter can be used to automatically set certain important computer vision parameters to avoid any “hand-tuning”.

## **Database: the bridge between experiment and computer vision**

To facilitate the transfer of data from experimental acquisition to image processing, a database is used to bridge the gap. The database not only stores each biological event (starlings flocking or midges swarming), but also standardizes the parameters used to describe each event and facilitates the retrieval of information about each event. For example event parameters of interest are: lenses used and intrinsic calibration parameters for lens/camera pair and extrinsic calibration parameters. The database has been designed to have various input forms to reduce errors during data entry for an event as well as an internet-based user interface to access the data base.

## **Software architecture**

The new software architecture can be described from top-down with respect to the processing steps for a given image sequence:

- Segmentation
- Static Matching
- Dynamic Matching
- Static 3D-Reconstruction
- Cluster Analysis
- Stereo Tracking: 3D-Trajectories

The relationship between these various software components is shown in Figure 3. Also shown in the figure is change status of each the component with respect to the StarFlag project. The remainder of this section highlights some of the key features of each software component listed above, with emphasis on new implemented strategies.

### *Segmentation*

From the images of a biological event, the image position of individual organisms can be determined using segmentation methods. For segmentation to be successful there must be some way to distinguish individuals from the background. Since the cameras used are grayscale, only contrast information can be used. Starlings when imaged appear dark against the sky (a light background), while for midges the opposite occurs i.e. midges are bright and the background is dark. Once the background has been identified, it can be removed from the image by subtraction (difference image). Next, a Gaussian denoising filter is applied to reduce both image sensor noise and artifacts from the background subtraction. A threshold is used to identify only those pixels representing individual organisms (binary image). The new feature of the segmentation component is the ability to select the threshold parameter from the properties of the image histogram of the difference image. From the binary image, pixels are clustered to form “blobs” that identify single or multiple organisms. Large blobs are split using a watershed mechanism. The lower resolution images of the current project contain more segmentation noise as compared to those obtained in the StarFlag project. This disadvantage means that more care has to be taken in setting certain parameters, but can be aided by examining global image features such as the image histogram. The higher temporal resolution of the captured image sequences has led to implementing this component using multi-threaded processes to perform parallel computing. So the images from each one of the three cameras can be processed simultaneously. Another issue exaggerated by the higher temporal resolution is “background movement”, which is not easily removed during background subtraction. A rejection method is implemented that removes any moving objects that do not belong to the flock or swarm by clustering all segmented objects and following the chosen animal cluster through all image sequences. An example of the results of segmentation of birds and midges are shown in Figures 4 and 5, respectively.

### *Static and Dynamic Matching*

The output of the segmentation process is a set of all segmented individuals of the analyzed sequence. These points then serve as the input for the static and dynamic matching algorithms. These two software components provide solutions for stereoscopic matching and tracking, respectively. Both components have as their core algorithm the same pattern recognition method used in the StarFlag project, but with added improvements. Specifically, due to the fully integrated framework, the parameters used in these algorithms can be set automatically using feedback fitting strategies. The effectiveness of the overall component is seen by the robustness of the final matches because of the increased number of images available which provide a solid statistical foundation.

### *3D-Reconstruction*

From the calculated stereo matches between cameras, their 3D position can be reconstructed using standard algorithms described in computer vision literature (for example minimizing the residual of a set of equations linking the coordinates of the stereoscopic image points to the 3D world coordinates of an individual). The extrinsic parameters from the calibration method described in the experimental summary are used in this calculation.

### *Cluster Analysis*

With the matching phase complete, connections between segmented individuals in different camera views at the same time instance (static matches) and in different time slices (dynamic matches) can be completed. From these connections, a graph can be constructed where the nodes represent a segmented individual and the links are formed by the static and dynamic matches. Each connected component of this graph is known as a “dynamic cluster”. Due to the simultaneous usage of static and dynamic



matches, links can be formed between the same individual in different cameras and at different times even if the individual is missing in certain frames because of segmentation problems (i.e. the individual was not found in a given frame due to noise or being occluded by others).

The connectivity of the graph provides robustness to this approach in that an individual can be recovered indirectly simply by following links. If all the matches in a dynamic cluster are correct, then it represents a real trajectory (full or partial) of an individual organism as shown in Figures 6 (birds) and 7 (midges). Note in Figure 6 the modulations in the trajectories, which are due to the flapping wings of the birds. This feature is only discoverable with the higher temporal resolution of the cameras. Due to mismatching errors the dynamic clusters typically contain entangled trajectories i.e. links form between two different dynamic clusters (see Figures 8 and 9). To measure the properties of the dynamic clusters, three parameters are defined: the number of frames in an image sequence is  $T$ , the average length of all dynamic clusters is  $L$ , and the average number of trajectories a given dynamic cluster are entangled with for its entire length is known as the thickness  $W$  (for a real trajectory  $W$  should be 1). Currently, analysis is ongoing on the best strategies to disentangle dynamic clusters and build longer dynamic clusters. The goal then is to have  $L$  as large as possible (ideally a ratio between  $L$  and  $T$  should be one) and  $W$  near to one (or at least less than a fixed threshold value).

A possible strategy to build longer dynamic clusters is to only use a subset of all the static and dynamic matches available, based on a given criteria such as coherence on stereoscopic and/or dynamic matches. For example, using only static links that have complete coherence between all three cameras (i.e. the same individual can be located and linked in each camera at the same time instance) or using all dynamic links with complete coherence (i.e. the same individual can be tracked across multiple frames in a single camera) over a set number of frames. To determine the most effective strategies, the average value of  $W$  for all clusters versus  $L$  for various strategies are plotted as shown in Figure 10 for a single image acquisition.

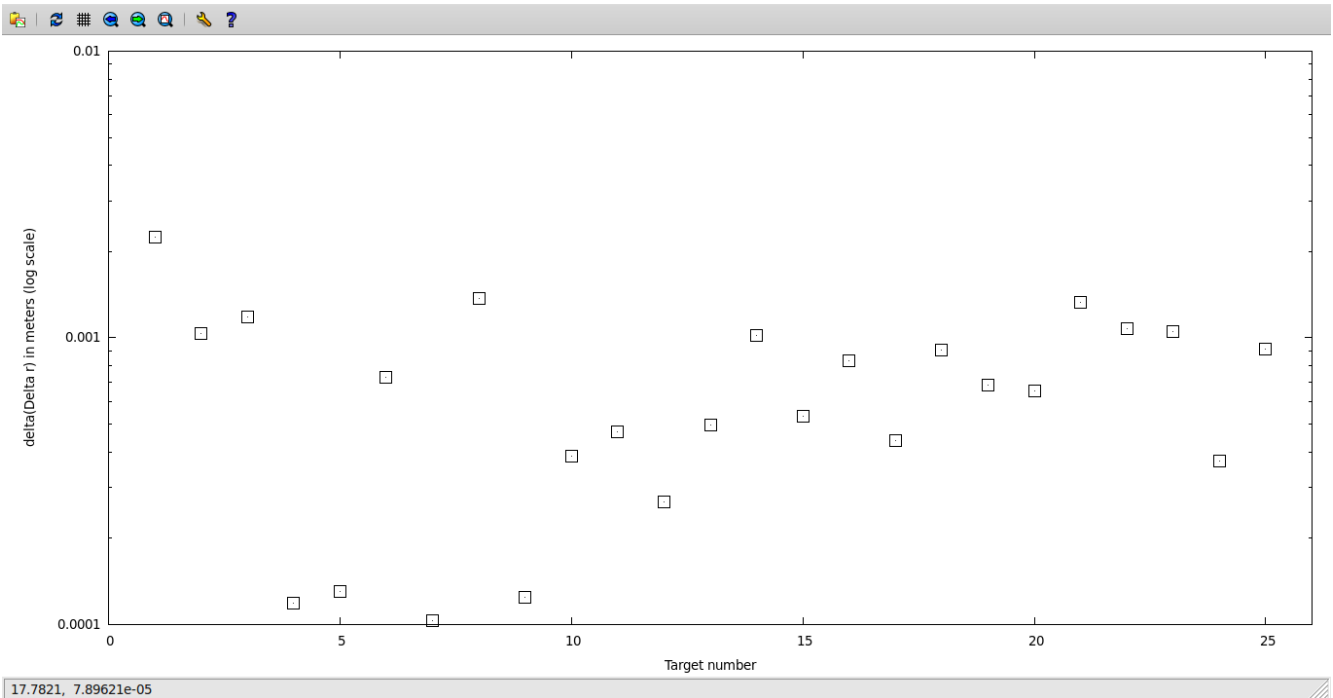
### *Stereo Tracking: 3D-Trajectories*

Once a “best strategy” is selected the dynamic clusters can be disentangled and trajectories formed by merging as many pieces as possible. This work is ongoing with the current solution to use a Monte Carlo algorithm with a cost function based on reducing the number of inter-cluster links. The disentanglement forms 2D real trajectories, but these can be translated in to 3D trajectories using the stereoscopic matches generated by the 3D Reconstruction component.

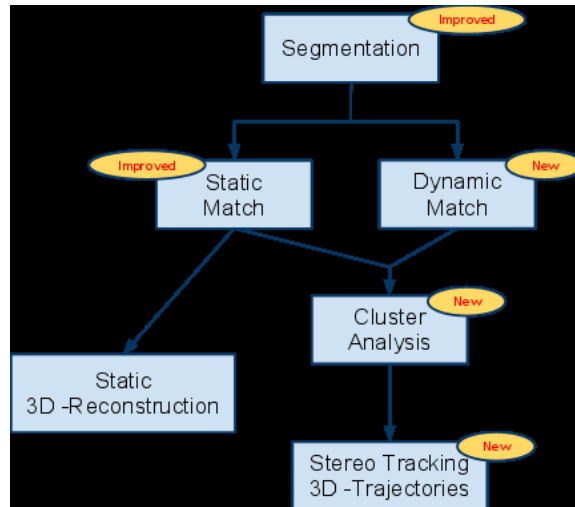
## Figures



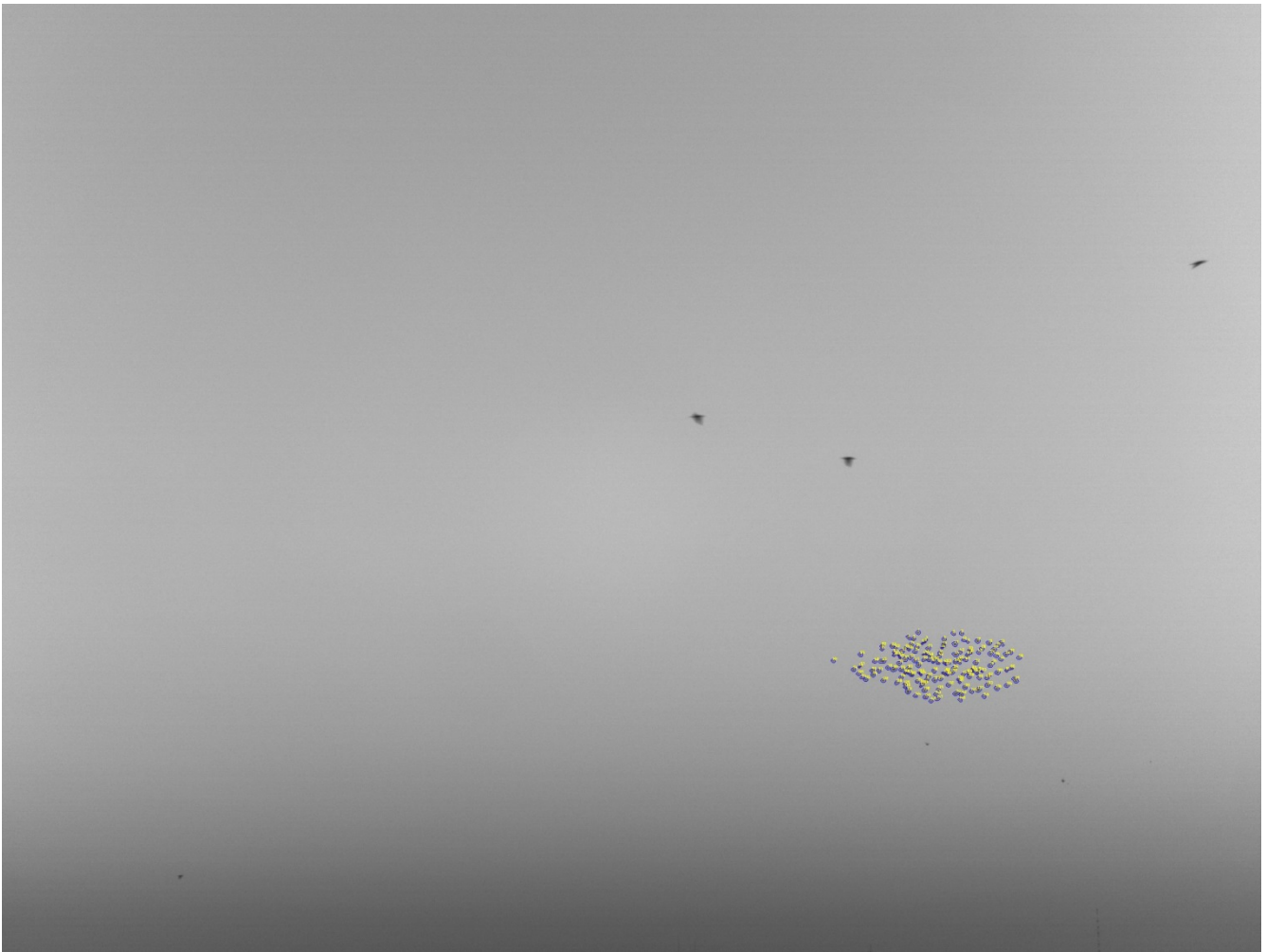
**Figure 1** (20110511\_cam3\_000002.jpg): Image for midge swarm extrinsic parameter calibration showing the new calibration target.



**Figure 2** (delta(Delta r).png): Typical absolute distance error between target centers of the extrinsic parameter calibration rig in real world coordinates. Distances are calculated from the optimal rotation and translation matrices returned by the zero temperature Monte Carlo algorithm.



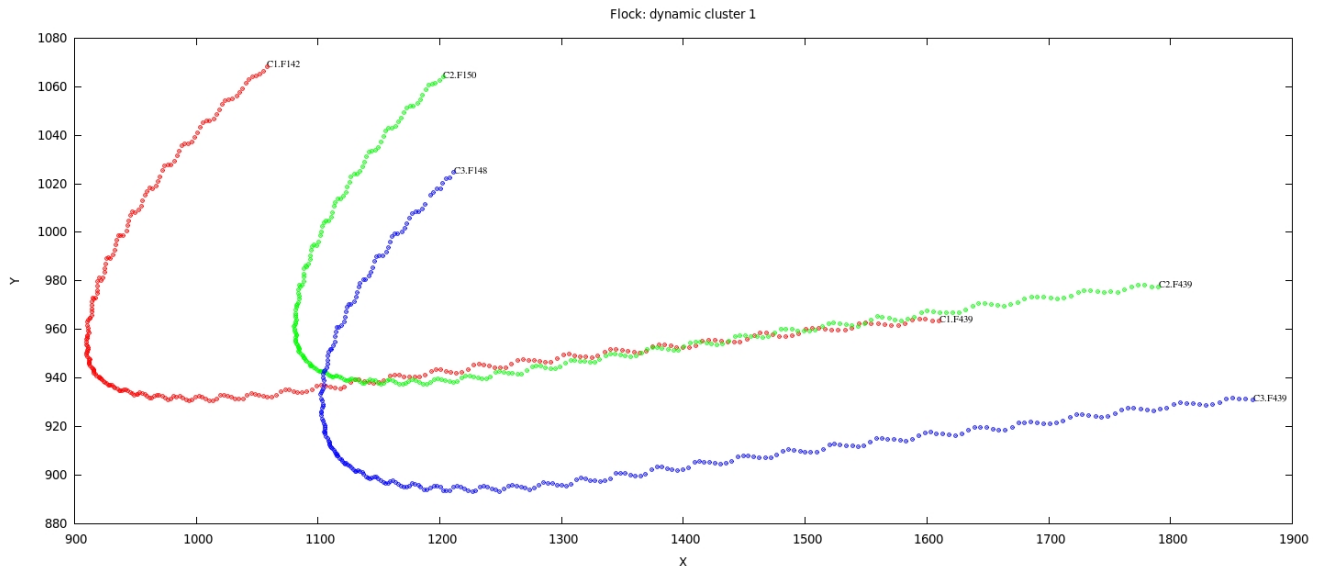
**Figure 3** (SW\_Architecture.pdf) : Software Architecture Hierarchy (The yellow balloons show if the software components are new or have been improved in the new project compared to the Starflag one).



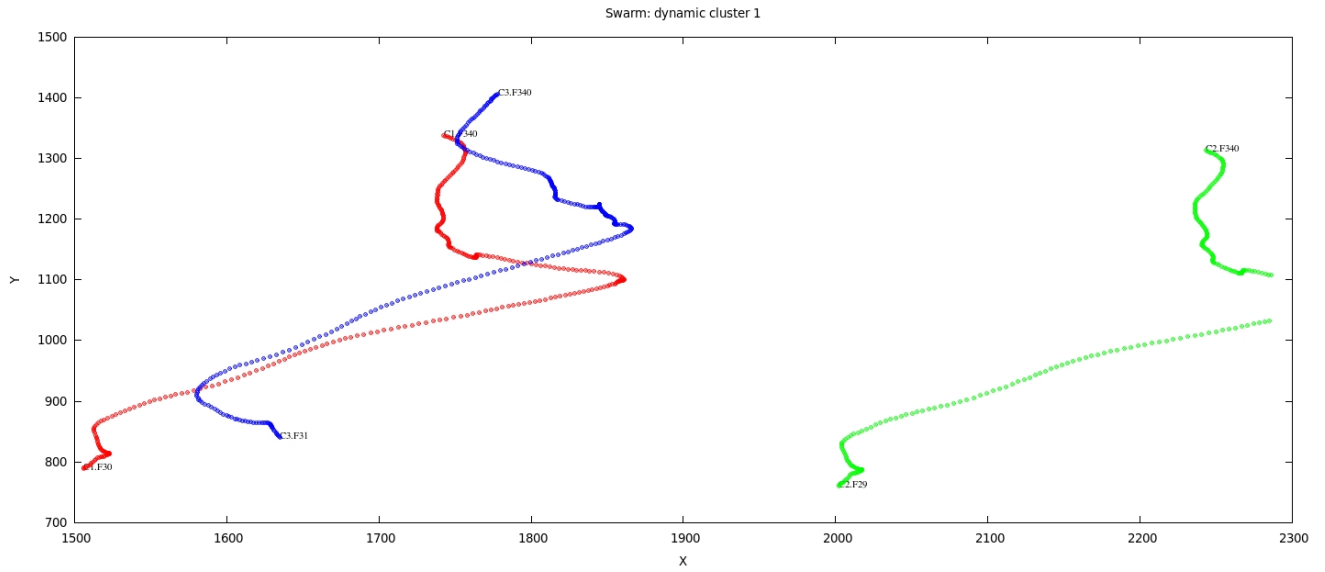
**Figure 4** (file: FLOCK.jpg): Typical flock of starlings, with segmented individuals numbered and highlighted with a blue contour.



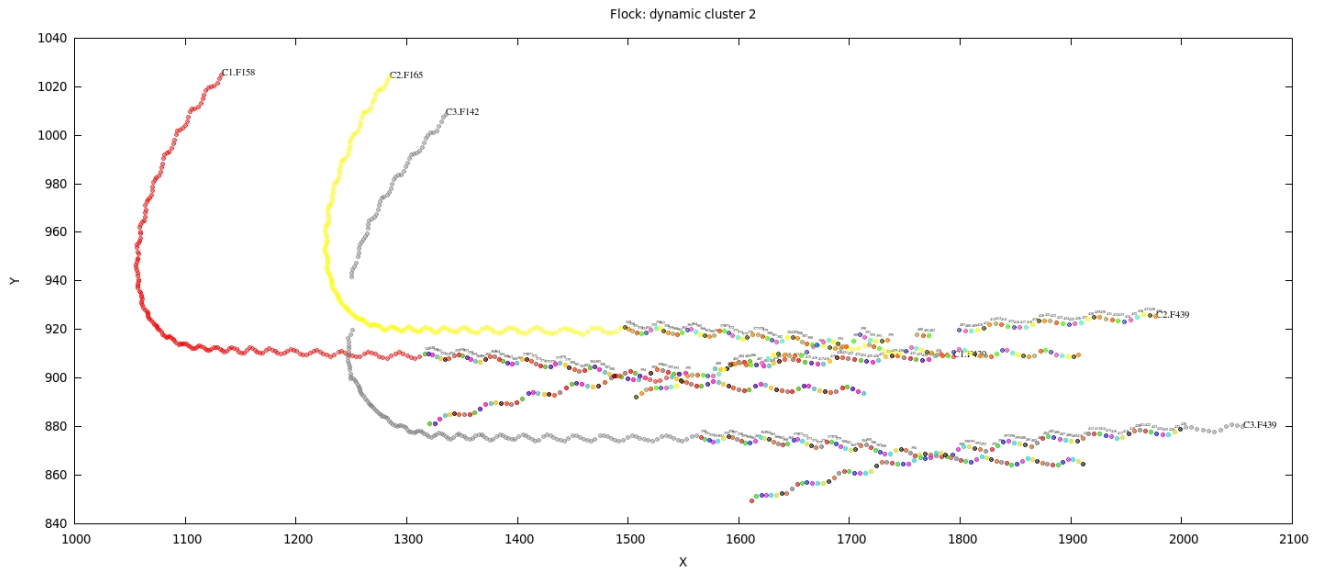
**Figure 5** (file: SWARM.jpg): Typical swarm of midges, with segmented individuals numbered and highlighted with a blue contour.



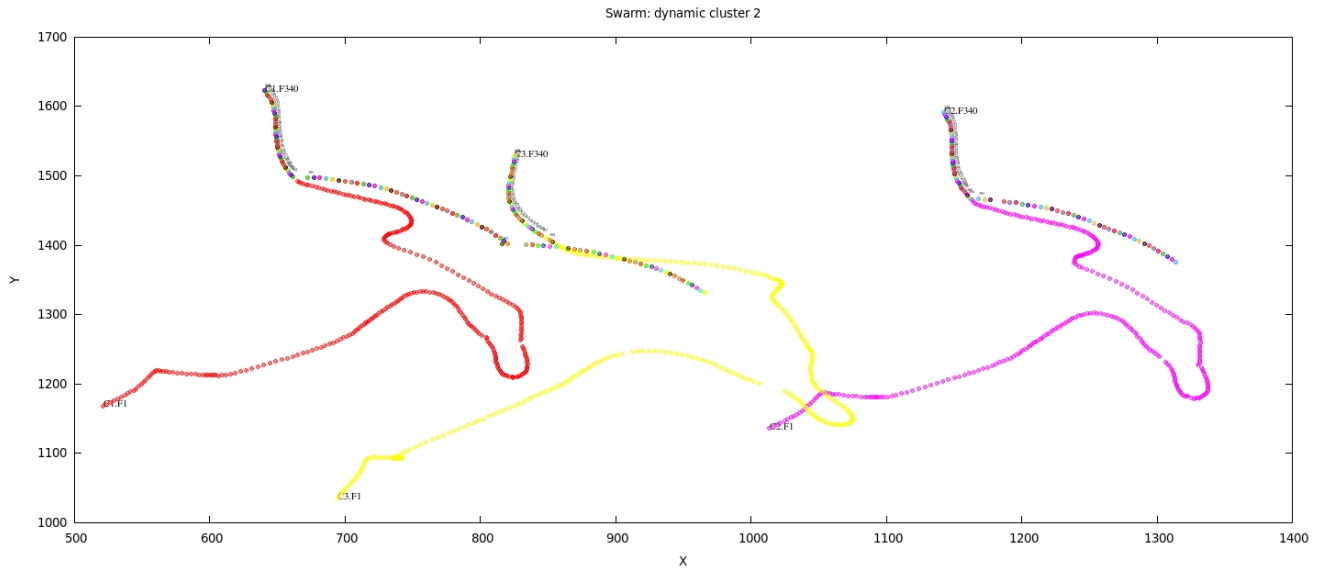
**Figure 6** (file: flock\_cluster\_1.jpg): A typical dynamic cluster of a starling acquisition; the three lines together represent a single real trajectory as seen by each of the three cameras. Each point of the line represents the baricenter coordinates of the bird obtained by the segmentation software. Note the modulation of the trajectory which is due to flapping wings of the bird, which is only discoverable with a high temporal resolution.



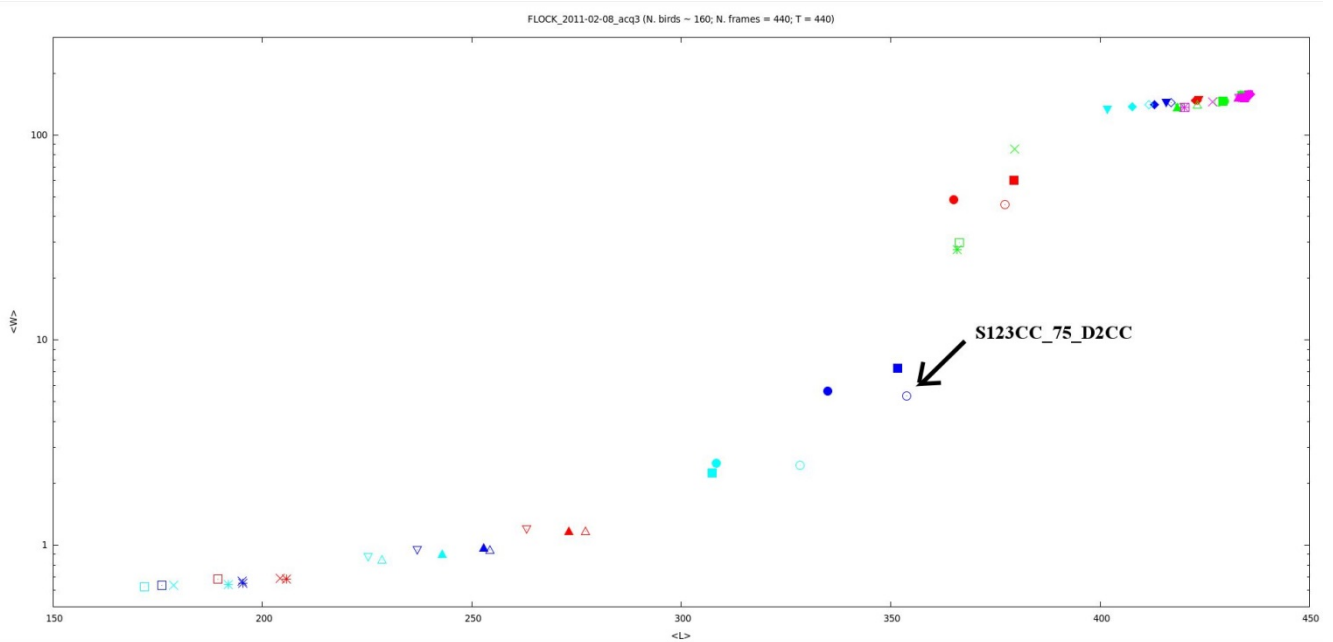
**Figure 7** (file: swarm\_cluster\_1.jpg): A typical dynamic cluster of a midge acquisition; the three lines together represent a single real trajectory as seen by each of the three cameras. Each point of the line represents the baricenter coordinates of the midge obtained by the segmentation software.



**Figure 8** (file: flock\_cluster\_2.jpg): A typical dynamic cluster of a starling acquisition; here there are entangled trajectories as shown by the multi-colored data points in each line. Birds belonging to different trajectories have the same color at the same frame for each camera. Each point of the line represents the baricenter coordinates of the bird obtained by the segmentation software. Note the modulation of the trajectory which is due to flapping wings of the bird, which is only discoverable with a high temporal resolution.



**Figure 9** (file: swarm\_cluster\_2.jpg): A dynamic cluster of a midge session; here there are entangled trajectories as shown by the multi-colored data points in each line. Midges belonging to different trajectories have the same color at the same frame for each camera. Each point of the line represents the baricenter coordinates of the midge obtained by the segmentation software.



**Figure 10** (file: Strategy\_W\_vs\_L.jpg): Average cluster thickness versus average cluster length for various cluster-building strategies (represented by different colored and shaped symbols). The black arrow indicates the “best” strategy for this session that gives long ( $L/T \sim 0.80$ ) and thick ( $W \sim 5.5$ ) clusters, which consists of using 75% of static links that are completely coherent and all dynamic links that are completely coherent up to two frame levels.

## Section 2 - Accomplishments during the second year of performance (2011-1012) the group of Co-PI Cavagna in Rome:

- Finished experimental data-taking campaign, both for birds and for midges.
- Developed a novel tracking method (with respect to the last reporting period) that led to solving a range of remaining computer vision problems and reconstruction of all individual trajectories in several flocks of starlings and midge swarms.
- The tracking algorithm was run on several flocking events, and on some swarming events.
- At the end of the second year 3D trajectories of starling flocks were delivered to the PI Krishnaprasad and his students for smoothing and extraction of curvature controls.
- Analyzed the data and developed new theoretical approaches and numerical models of collective animal behavior.
- Wrote, submitted and published results in high profile peer-reviewed journals.

## Deliverables

At the end of the reporting period (more precisely on May 30th, 2012), Co-PI Cavagna, head of the ISC-CNR unit, traveled to the US, Maryland and discussed with the PI Krishnaprasad (UMD) the state of the project. In that occasion, Cavagna delivered to the PI a set of reconstructed 3d trajectories of flocking birds. These are the delivered events, with their specifications:

- 20111209 - 20 birds - 8.8 secs @ 170 fps
- 20111125 - 50 birds - 5.9 secs @ 170 fps
- 20111222 - 60 birds - 3.6 secs @ 170 fps
- 20110208 - 179 birds - 5.5 secs @ 80 fps

## Publications Status at this stage of the project was as follows

1. *Statistical mechanics of natural flocks of birds* W. Bialek, A. Cavagna, I. Giardina, T. Mora, E. Silvestri, M. Viale, A. Walczak, **Proc. Natl. Acad. Sci. US** 109, 4786 (2012)
2. *Starling flock networks manage uncertainty in consensus at low cost* G F. Young, L. Scardovi, A. Cavagna, I. Giardina, N. E. Leonard (first Submitted in March 2012 - Published in Feb 2013 in **PLOS Computational Biology** 9 (1), e1002894)
3. *Spatially balanced topological interaction grants optimal cohesion in flocking models* M. Camperi, A. Cavagna, I. Giardina, G. Parisi, E. Silvestri, **Interface Focus** 10.1098/rsfs.2012.0026 (2012)

4. *Diffusion in starling flocks* A. Cavagna, S. M. Duarte Queiros, I. Giardina, F. Stefanini and M. Viale ArXiv:1206443 (published in Feb 2013 in **Proc. Royal. Soc. B** 280, 1756)
5. *Boundary information inflow enhances correlation in flocking* A. Cavagna, I. Giardina, F. Ginelli ArXiv: 0502936 (accepted in **Physical Review Letters** - to be published 2013)

## Data Gathering Experiments Conducted by Co-PI's group

### Introduction

From June 2011 to June 2012 experiments on starling flocks and midge swarms were carried out on a daily basis. Equipment, experimental set-up and calibration software of intrinsic and extrinsic camera parameters were the same as the previous year. Flocking and swarming events were captured using a system of three synchronized high speed cameras IDT M5. Two of these cameras, the stereometric pair, are placed 25m apart for birds and about 3m apart for midges. A third camera sits at a shorter distance from a stereometric one (2.5m for birds and 0.25m for midges). Set-up for midges included also an omnidirectional hot-wire anemometer synchronized with the camera system. It is positioned as close as possible to the swarm, so that a measure of the wind speed nearby the swarm can be retrieved and gusts of wind can be detected. Fig. 1 shows a typical set-up in the field for midges experiment.

### Starling Flocks

New data on starling flocks were acquired from December 2011 to February 2012. The main location for the experiment was Piazza dei Cinquecento on the roof of Palazzo Massimo. Unfortunately, due to unknown biological reasons, birds moved from the roosting site in Piazza dei Cinquecento on January. This forced the experiment to be moved to another roosting location, K\_Building of Poste Italiane Headquarters in Eur, where the experimental set-up was limited to a non-ideal area. Hence, few events were captured at this location.

The experiment on flocks was focused in particular on two different goals: big flocks (up to thousand birds), and flocks which are turning. To achieve the first goal, new lenses were needed. In fact, due to their narrow field of view, Schneider 28mm were not suitable for this purpose. In particular Zeiss Distagon T\* 25mm, Zeiss Distagon T\* 21mm, Kowa LM16XC 16mm were tested and used on the field. During turns, the probability of optical occlusions is higher than in a flock passing straight in the field of view. In order to have more details during turns, a frame rate of 170 fps was chosen, instead of 80 fps as in the previous year.

The total number of acquisitions is 65 and among them 53 are of high quality. Histogram in Fig. 2 shows number of usable and non-usable acquisitions comparing season 2010-2011 with the current one. From this plot, it is clear that in this last year the percentage of high quality acquisitions increased considerably, even if the total number of recorded events is much smaller than the previous year.



## Midge Swarms

Swarming events were recorded in Villa Paganini, Villa Ada, Parco degli Acquedotti, Laghetto dell'Eur. Midge pictures are taken using back-scattering sunlight, and a dark, uniform, stationary background is needed to provide high contrast. Taking pictures using back-scattering implies having cameras almost in front of the sun, with a consequent glare in the pictures. Glare dramatically reduces image quality. In fact, whenever a midge passes in front of a glared region it disappears and it is not possible to retrieve its trajectory. Black PVC lens hood, 0.45m long, were built in home and used to reduce glare effect on the pictures.

A black fabric background, 3x15m in size is mounted behind the swarm, see Fig. 1, to improve contrast, to cover bright objects (i.e. grass, leaves) and to avoid moving faraway objects (i.e. people, cars) in the pictures. Picture quality was also improved using IR filters, to reduce IR-radiation passing through the background fabric.

Artificial background and IR filters are not always sufficient to record a usable acquisition. Swarms often occur at the interface between sunlight and shadow. This can create problems in the identification of midges when in the shade, due to the low contrast. A very useful tool is a landmark, with which the swarm could be moved to a suitable position. Several landmarks were tested, such as plywood squares with black and white features or black and white cardboard. The landmark that works better, in particular with *Chironomidae*, is a reflective aluminum/plastic wind-shield sunscreen. Using this landmark, an already formed swarm can be easily moved to a desired location. Moreover, this landmark is a very effective midge attractor. So, it can be used to induce the formation of a swarm in the best position for the experiment.

The total number of acquired swarm events is 90. Histogram in Fig. 3 shows distributions of acquisitions grouped by overall mark and size of the swarm. As this histogram shows, most of the recorded events are of small size swarms, up to 50 midges. In the future midge experiment will be focused on capturing large swarm events, with more than 200 individuals.

## Midge identification

For each session in the field, a few midges from the swarm of interest are caught with a net and preserved in 75% alcohol in PRC tubes. These samples are then analyzed in the laboratory to identify the midge. Identification is a complex and time-consuming process. Midges studied by our group are divided into two families *Ceratopogonidae* and *Chironomidae*, and their family is easily identified looking at antennas. Once the family is known, many details of the midge components (wings, eyes, legs) have to be observed to find its genus. In particular, looking at the *hypopigium* (male sexual organ), it is possible to uniquely identify a midge. Two microscopes are used for this purpose. Some characteristics are observed through a stereometric microscope, but minute details can only be seen with an optical microscope, with the midge mounted on a glass slide.

Samples caught during the reporting period (2011-2012) season belong to both families, *Ceratopogonidae* and *Chironomidae*. Most of them are *Chironomidae* and among them only two subfamilies were found till now, *Orthoclaadiinae* and *Chironominae*. Going further down in the taxonomy, several tribes were discovered. Among *Ceratopogonidae*, both the subfamilies *Dashyelea* and *Forcipomyia* were found. In Fig.4, a male and a female of *Isocladius sylvestris*, family *Chironomidae*, subfamily *Orthoclaadiinae* tribe *Cricotopus*, one of the most frequent caught midges are shown.

## Tracking

### Introduction

The Artswarm Computer Vision team developed a novel tracking algorithm in the period 2011, June 1st - 2012, May 30th. The development of the new algorithm has been deemed necessary in order to overcome some of the limitations of the previous algorithm, improve the tracking results of flocking birds obtained during the previous year, and solve the problems inherent to a different kind of experimental data: swarming midges.

The architecture of the previous tracking software was based on six processing steps: segmentation; static matching; dynamic matching; cluster analysis; stereo tracking; static 3D-reconstruction. The current software uses exactly the same modules to perform the segmentation and the static 3D-reconstruction steps, while the two matching modules and the tracking module have been completely redesigned.

The quality of the 3D-trajectories of flocking birds recovered with the new software improved significantly compared to the results of the previous year. The improvement is seen in terms of trajectory length (reduced trajectory fragmentation), total number of tracked objects (larger flocks, above 1000 individuals), and acquisition duration (events longer than 1000 frames).

### Limitations of the old software

The software developed in the first reporting period was not able to cope with long-lasting optical occlusions, due to a pure one-to-one linking which forces every object detected in the images to belong to only one trajectory. In Fig. 5, we show a scheme of a partial temporal sequence of two objects A and B as seen by one camera. The two objects overlap in the image for one or more frames, three in the example. The old algorithm would assign only one dynamic link to each detected object, therefore the points of occlusion would belong to only one uninterrupted trajectory, while the second recovered trajectory would result as a broken one. This produced a severe trajectory fragmentation. The study of large groups of animals and, in particular, the analysis of the interactions among individuals, can be strongly biased by fragmented and missing trajectories in the reconstructed data. Therefore it is of utmost importance to track all individuals, without losing their identities within the duration of the entire acquisition, even when their optical density in the images becomes important.

### A novel tracking approach

The new algorithm is based on three main ideas:

1. The bifurcation of dynamical links and the construction of all possible paths (Fig 7). In the example in Fig.6 the assignment of multiple links results in four uninterrupted paths, of which two are real trajectories and two are hybrid. Therefore we need a criterion to select the two right trajectories.
2. A global optimization criterion to select the correct paths out of all possible paths.
3. A recursive algorithm, which breaks the entire temporal sequence into shorter intervals, and iteratively combines the partial solutions into the full one.

### **Static and dynamic linking**

The strategy to find both static (stereo) and dynamical links is essentially the same as in the old algorithm, but with one crucial difference. Previously, given an object and a set of potentially good links connecting this object to another one, we had to pick up one, using some quality criterion. Now, we take all of them, both at the stereo and at the dynamical level. Once this is done, we percolate all the dynamical links across the whole acquisition, and we build *all* possible paths (Fig.7). The correct trajectory is certainly within this pool of paths, we simply have to select it. This is done by the global optimization.

### **Global optimization**

In Fig. 8, we explain graphically how the optimization selects the two correct traces over the four candidates proposed by the multiple link assignment in Fig. 6. In the example, the score function is defined as the sum of the static links between the points of each 2D-trace in different views. The traces of the two real objects A and B partly overlap in the left camera view, generating four possible paths. On the other hand in the right camera there is no overlap, so there are only 2 paths. To each pair of left-right paths is assigned a score proportional to the number of stereo link (same color) connecting the pair. Then, a global optimization is performed, finding the assignment that maximizes the score. Optimization is performed using the C++ APIs of IBM ILOG CPLEX Optimization Studio v12.2.

### **Recursive strategy**

The number of possible paths obtained percolating the dynamic links grows exponentially with the time duration of the acquisition (typically hundreds or thousands of frames). Indeed, the number of possible paths  $N^*$  can be estimated as  $N^* = N e^{(bT)}$ , where  $N$  is the number of objects,  $T$  the duration of the acquisition, and  $b$  the bifurcation coefficient. Fig. 9 reports the actual number of possible paths for a typical acquisition of roughly 179 birds as a function of the considered duration  $T$  (each dot refers to one interval of  $T$  frames).

To reduce this exponential complexity, we implemented a recursive algorithm. The acquisition is divided into temporal intervals with length  $T_1 < T$ , over which the complexity of the problem can be handled. The global assignment is performed over each interval. Considering the resulting matched 2D-traces of objects as meta-objects, the procedure is iterated to match the 2D-traces of

meta-objects across the different views and over time intervals of length  $T_2$  meta-objects. As shown in Fig. 10, the procedure is applied recursively, until the product of the duration of the intervals of each iteration equals the duration of the entire acquisition,  $T_1 T_2 \dots T_k = T$ , so that the partial solutions retrieved at each iteration are combined into the solution of the full problem at the last  $k$ -th iteration.

## Results

The implemented algorithm has been tested in processing 11 field acquisitions of flocking birds (see Table 1), and 2 field acquisitions of swarming insects.

We show the reconstructed trajectories for one of the events, the bird flock labeled 20111125\_a2\_e07 in Table 1. In Fig. 11, the 2D-traces reconstructed in the image-space of each of the three cameras used to acquire the event are shown for a single bird. Fig. 12 shows the reconstructed 3D-trajectory of the same bird. In Fig. 14, we report the normalized lengths distribution of the reconstructed trajectories for five bird flock events. As shown, the distributions are strongly peaked towards 1, indicating that the majority of the reconstructed trajectories are full-length ones and the trajectory fragmentation is negligible.

Fig. 15 shows the reconstructed trajectories for an analyzed event of swarming midges (roughly 100 midges, 2200 frames). The new algorithm improved considerably the quality of the results, and further development of the algorithm and optimal tuning of its parameters to process midge swarm data is ongoing.

## Data analysis and theoretical description

### Maximum Entropy Approach

One of the main objectives of our work is to use experimental data to infer information on the mechanisms regulating collective behavior, in particular the interactions at play between individuals. The first step in this program is to measure relevant statistical observables, and eventually use them as a starting point for inference methods. In a previous work, we measured correlations between individual velocities in starling flocks, and found that they are scale free and unusually strong, both for what concerns correlations between flight directions and correlation between speeds. This means that a behavioral change in direction or speed of one bird in the flock influences all other individuals in the group. Clearly this feature is crucial to grant the group efficiency in response and coherence, but its microscopic origins were not understood.

In the reporting period we developed new theoretical techniques for statistical inference based on the Maximum Entropy approach, and applied this method to starling flocks using experimental correlations of flight directions as an input. In this way, we showed that the interactions between individuals giving rise to the experimentally observed correlations are local, pairwise, and depending on the topological distance. From the data we were also able to the strength and the range of the interactions. The model we built using the maximum entropy method finally fits perfectly well the observed correlation functions, with no free fitting

parameters. **Publication #1: Bialek et al.**

### **Robustness of consensus in flocks**

We addressed the issue of stability and robustness of the cohesion displayed by starling flocks. A few years ago, we discovered that interactions between individuals in a flock are topological, each bird interacting approximately with the seven proximate neighbors irrespective of mutual distances. We suggested this kind of interactions could be functional to ensure robust cohesion to the flock. During the reporting period we worked to consolidate this conclusion by using control theory methods. Using experimental data on individual positions, we analyzed robustness to uncertainty in multiple flocks and showed that interaction networks with 7 neighbors optimize the trade-off between group cohesion and individual effort to keep track of the neighbors. This result is quite remarkable, as it has been discovered on starling flocks, but it can be applied to any other kind of network, both natural and artificial, showing the immense interdisciplinary potential of studying collective animal behavior. **Publication #2: Young et al.**

### **A new spatially balanced model**

Numerical models are a powerful tool to investigate hypothesis suggested by experiments, and fully understand the mechanisms leading to the behavior that we observe. As mentioned above, we found that interactions in flocking birds have a topological rather than a metric nature, and speculated that this kind of interactions is able to grant the group a more robust cohesion. To test this conclusion, we considered 3D flocking models with different interaction rules, either metric or topological, and asked what kind of rules performed more efficiently in terms of cohesion. By comparing the response of the system to obstacles and noise, we concluded that spatially balanced topological interactions grant optimal cohesion to the group. This means that the individuals each bird chooses to interact with must be evenly distributed around it. This kind of interaction grants a much higher cohesion of the network. **Publication #3: Camperi et al.**

### **Diffusion**

All the statistical analysis described so far, exploits data on individual 3D positions and velocities. Availability of 3D trajectories, made possible by the AFOSR funding, opens new opportunities of investigation. One important aspect of collective motion is related to the fact that individuals continuously move and exchange positions. The dynamical nature of the interaction network and its role in stabilizing global ordering have been discussed theoretically, but never measured in real flocks. We have measured the diffusion properties in starling flocks and quantified the dynamics of the adjacency network between individuals, discussing consistency with theoretical and numerical predictions. We find that birds have a superdiffusive motion (i.e. faster than a random walk) in the reference frame of the flock, and that this ensures that neighbors' reshuffling does happen. Therefore, the interaction network is not static. However, we also find that the time scale over which such reshuffling takes place is quite slow, when compared to the individual relaxation time. We concluded that the enhancement of the interaction due to this dynamical effect is probably smaller than expected in bird flocks.

## **Publication #4: Cavagna et al.**

### **Anomalous long-range correlations**

Another interesting problem concerns the behavior of velocity correlations in starling flocks. These correlations are unusually strong, a feature that cannot be explained within existing theories and models. We put forward the hypothesis that the slow decay of the correlation might be due to an information transfer from the boundary to the bulk of the flock. To investigate this issue, we performed numerical simulations on a simple alignment model subject to a dynamical perturbation on the boundary. We showed that, under appropriate conditions, the effect of the perturbation is to trigger anomalously long-range correlations, as the ones experimentally observed. This result seems to imply that flocks are always close to some state of dynamical excitation, where a continuous change of state, and its consequence transfer of information from one side to another of the flock, achieves the crucial result to keep the whole flock highly correlated in space. **Publication #5: Cavagna et al.**

### **Collective decision-making**

At the end of the reporting period we started addressing one of the most intriguing aspects of self-organized collective behavior, namely the process of group decision-making. What is that triggers a collective decision? How is the decision transferred to all individuals? These questions are difficult to answer experimentally, as they require a complete reconstruction of individual trajectories in large groups and for long enough timescales. Luckily, our novel 3D tracking algorithm (see Section : Tracking) allowed us to achieve such result. Using the newly retrieved 3D trajectories for flocking birds, we could quantitatively characterize the formation (from individual actions) and the spreading of a collective decision. More precisely, we are focusing on collective turns of flocks. Our preliminary results are very exciting, as we seem to find a new set of equations, describing collective turns, which are very reminiscent of superfluid theory in condensed matter. We are at present consolidating our results by analyzing more events, and expect to submit a paper to a high-impact journal in a few months.

### **Ongoing work.**

### **Maximum entropy on speed correlations**

We are generalizing the maximum entropy approach to address not only flight directions but also individual speeds. Interestingly, preliminary results indicate that flocks are very close to a critical point. In other terms, the scale-free correlations between speeds that we observed experimentally are a quasi-critical effect. A very debated and open question is whether biological systems are poised to criticality, and whether there are deep theoretical and adaptive principles behind this. Our results are likely to give a strong contribution to this issue. At the same time, we are developing a numerical model with variable individual speeds directly inspired by the maximum entropy approach results.

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Figure 1- Typical set-up for midge experiment

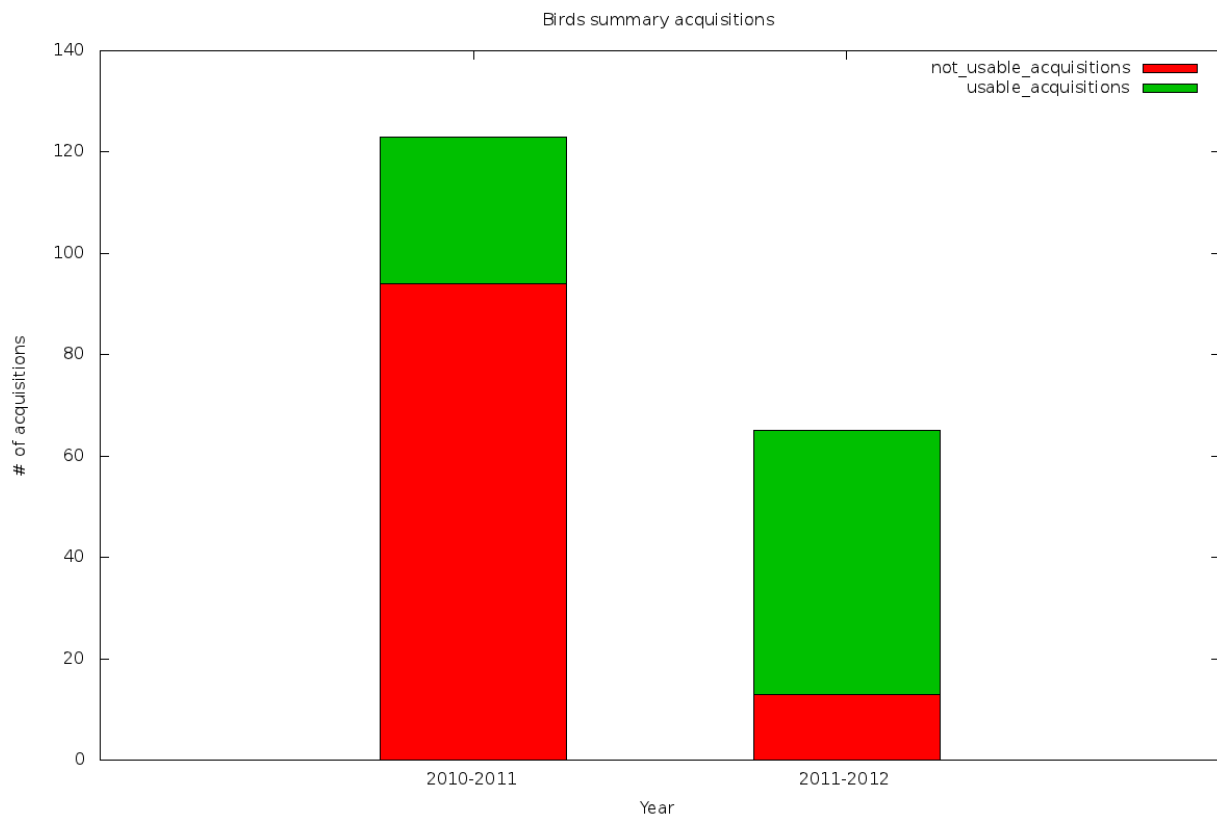


Figure 2 - Comparison between 2010-2011 season and 2011-2012 season for birds. Percentage of usable acquisitions increased in the current year even if the total number of recorded events is lower.



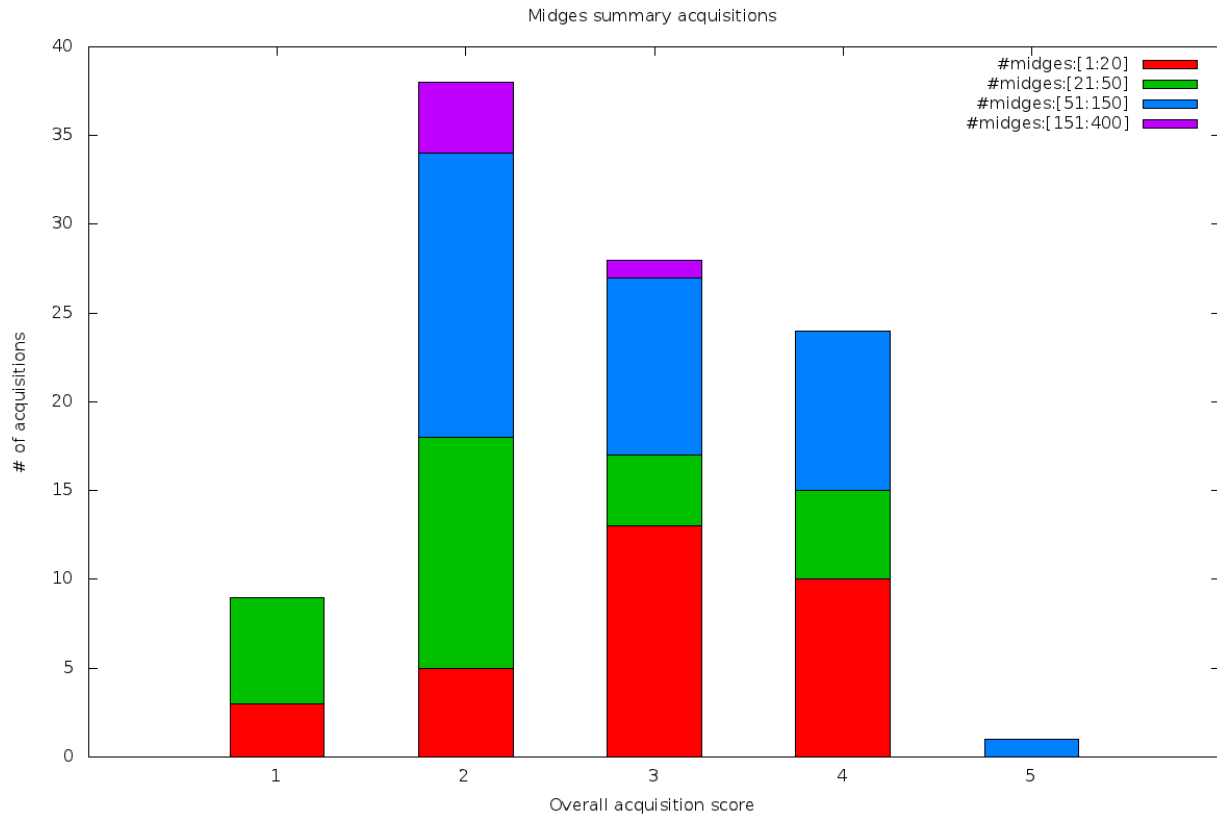


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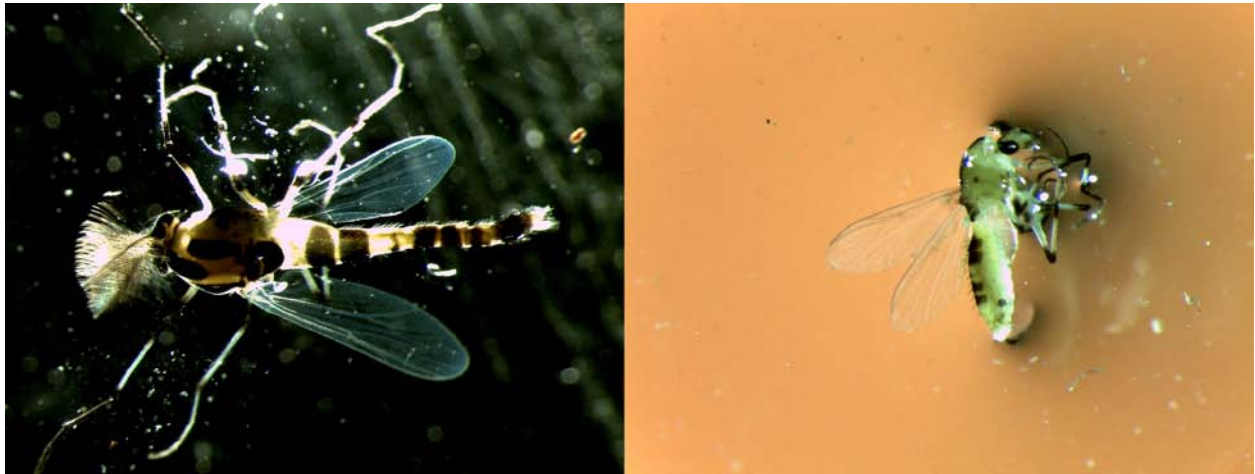


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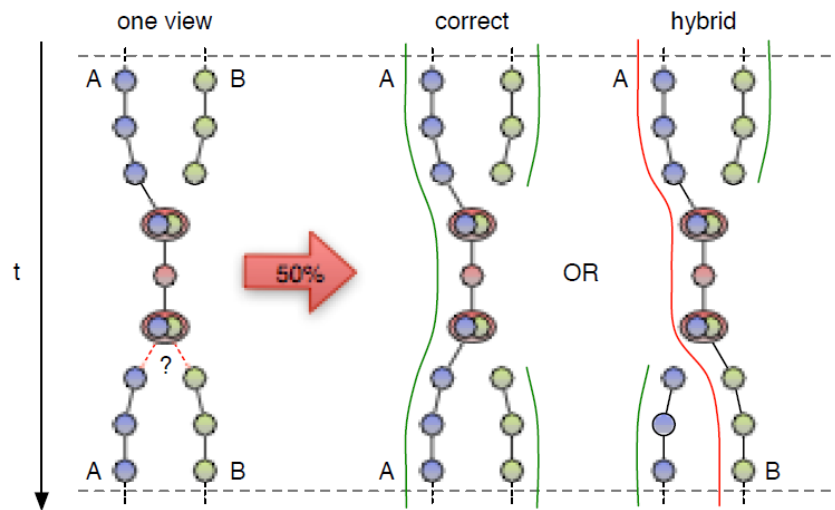


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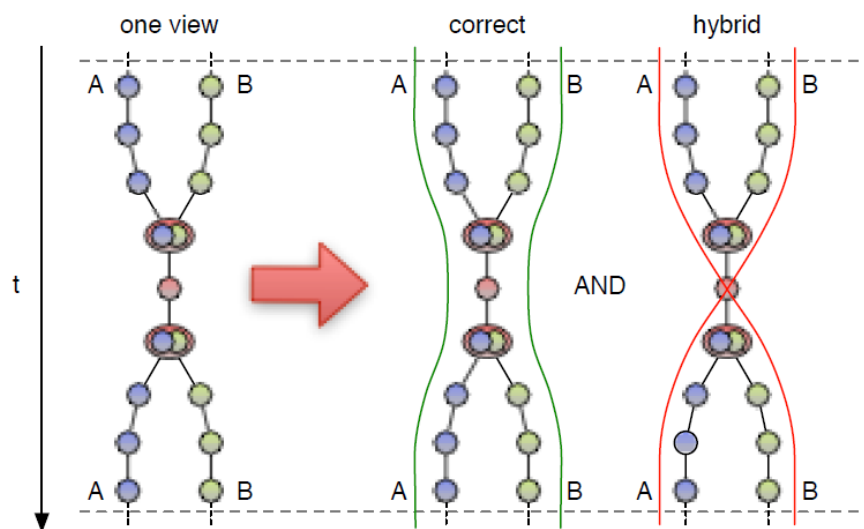


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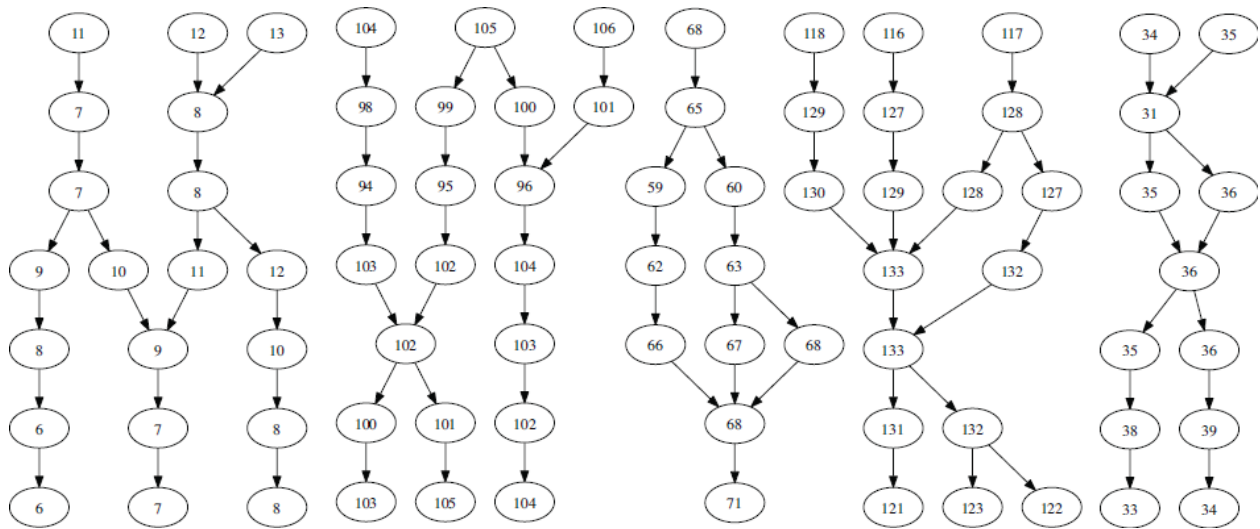


Figure 7 - Percolated dynamic links, producing the possible paths of a few birds over a few consecutive frames in time.

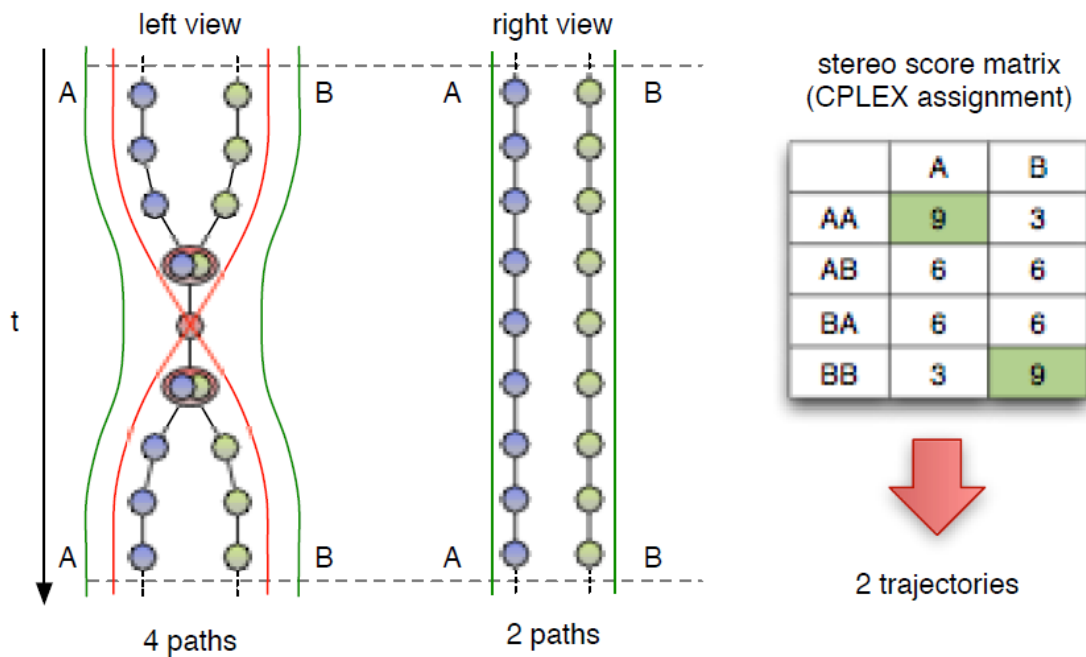


Figure 8 - Scheme of the global optimization strategy applied to select the correct paths between the four possible paths extracted in the example of Fig. 6.

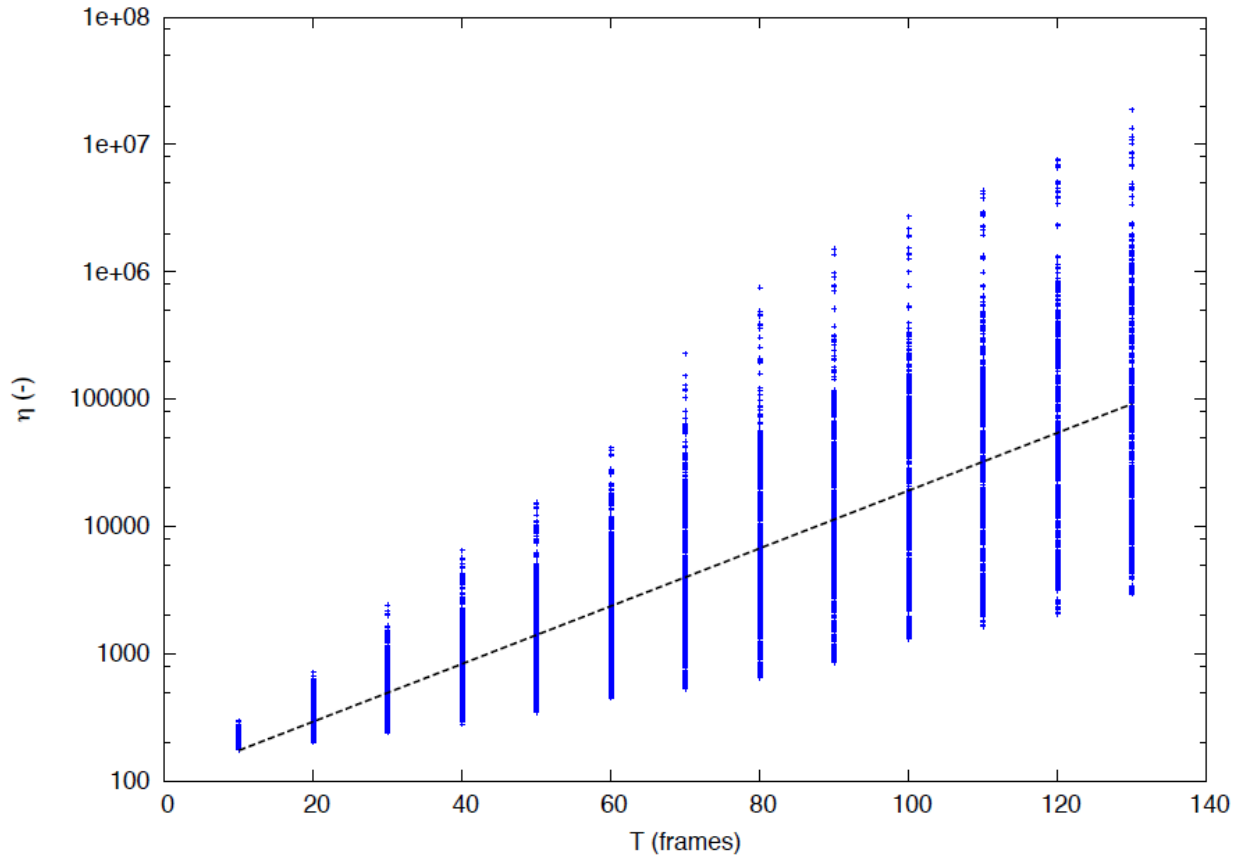


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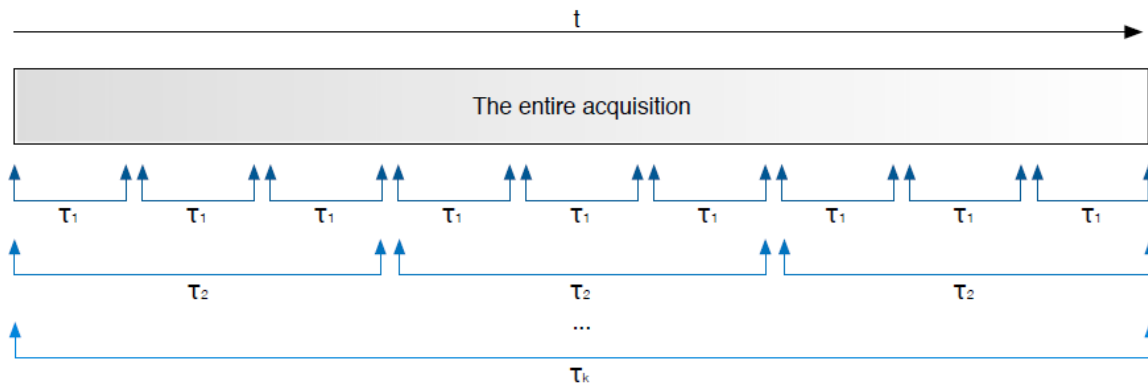


Figure 10 - Scheme illustrating the recursive approach.

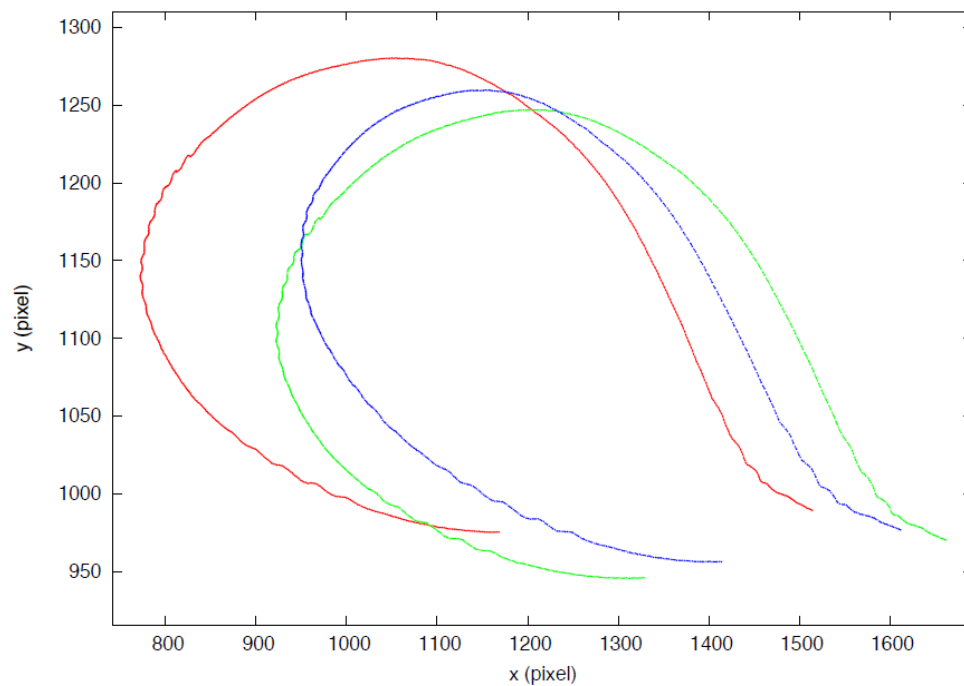


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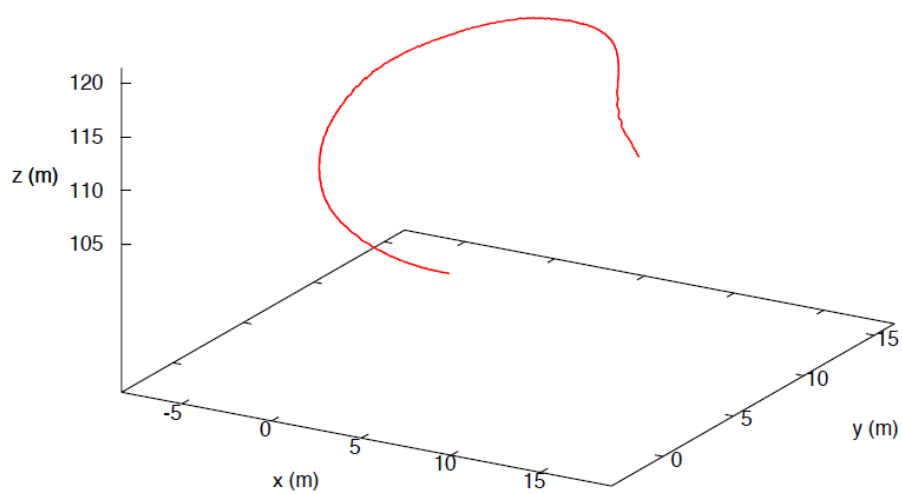


Figure 12 - 3D-trajectory of the same bird of the event 20111125\_a2\_e07 shown in Fig. 11.

Figure 13 - 3D-trajectories of the entire flock (roughly 481 birds) of the event 20111125\_a2\_e07 (**file too large - available upon request**).

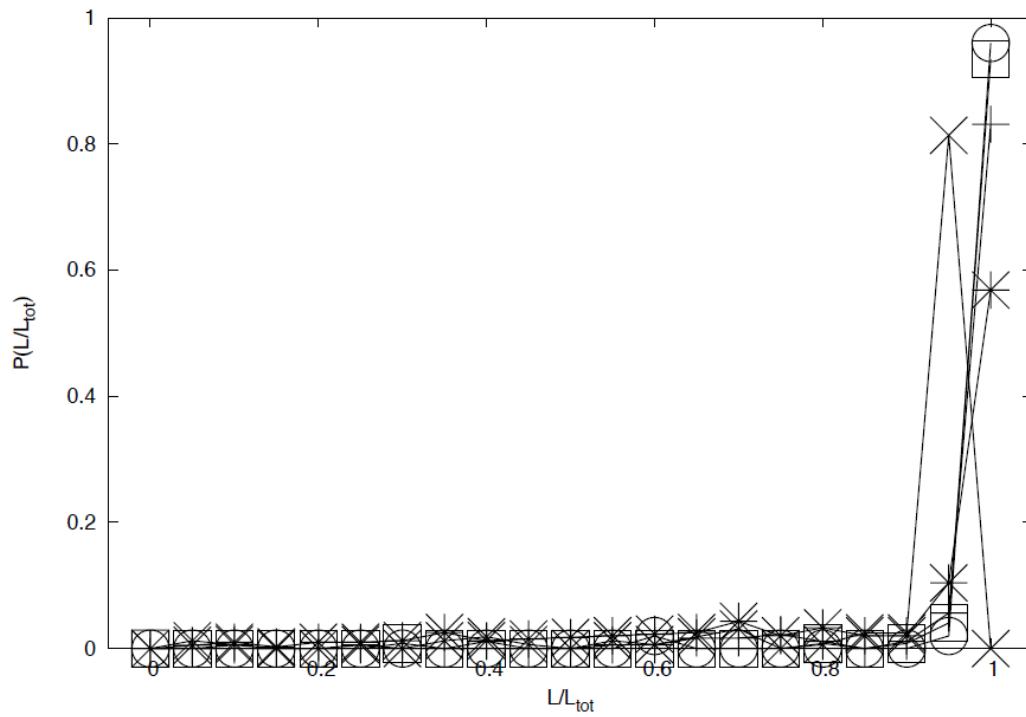


Figure 14 - Normalized lengths distribution of the reconstructed trajectories for five bird flock events.

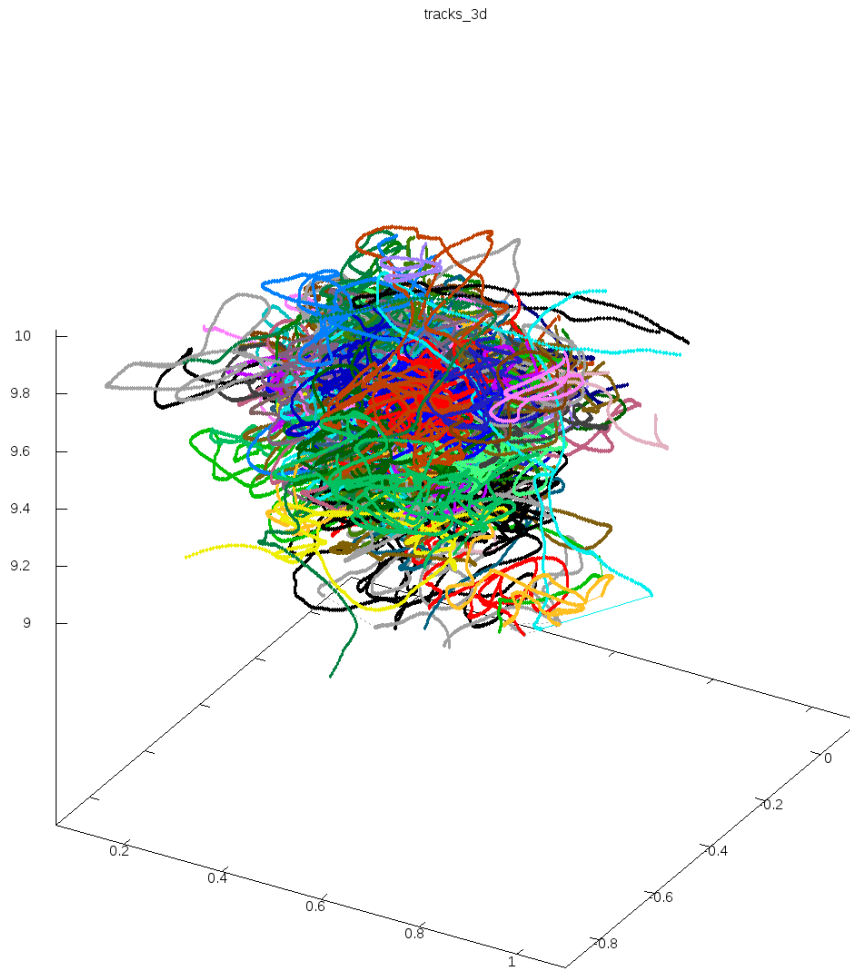


Figure 15 - 3D-trajectories of a midge swarm event (roughly 100 midges).

	duration (frames)	duration (sec)	est. #	# output	FPS	turn	elab. time
20110208 a3_e13	440	5.5	179	179	80	YES	1013
20111209 a1_e04	1490	8.8	19	20	170	YES delta	4253
20111125 a1_e03	1000	5.9	50	49	170	YES	2122
20111124 a1_e06	310	1.8	120	124	170	YES	368
20111214 a4_e13	1080	6.3	153	164	170	YES	42655
20111222 a1_e01	609	3.6	60	59	170	?	177
20111214 a4_f2_e03	708	4.2	148	148	170	YES	1679
20120209 a1_e05	600	3.5	396	412	170	NO	12500
20111125 a2_e07	365	2.1	481	485	170	YES	1874
20111215 a1_e07	960	5.6	381	385	170	YES	14421
20111207 a1_e01	661	3.9	110	111	170	YES	554

Table 1 – Performance of the implemented algorithm in processing 11 field acquisitions of flocking birds.



### **Section 3 - Accomplishments during the third year of performance (2012-2013) of the group of Co-PI Cavagna in Rome:**

During this period Cavagna and his group

- Extended the experimental data-taking campaign for midges to collect audio and video synchronous data.
- Implemented some modifications to the tracking software and found the optimal tracking parameters for midge data.
- Ran tracking algorithm on new flocking and swarming events.
- Analyzed the data and developed new theoretical approaches and numerical models of collective animal behavior.
- Wrote and submitted the results of the work in high profile peer-reviewed journals.

### **Publications**

- (1) A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, T.S. Grigera, A. Jelic, S. Melillo, L. Parisi, O. Pohl, E. Shen, and M. Viale, *Superfluid transport of information in turning flocks of starlings*. arXiv:1303.7097 [cond-mat.stat-mech] (2013). Manuscript submitted to *Science*.
- (2) A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, A. Jelic, S. Melillo, L. Parisi, E. Shen, E. Silvestri, M. Viale, *Tracking in three dimensions via multi-path branching*. arXiv:1305.1495 [q-bio.QM] (2013). Manuscript submitted to Transaction of Pattern Analysis and Machine Intelligence.
- (3) A. Cavagna and I. Giardina, *Bird flocks as condensed matter systems*. Annual Review of Condensed Matter Physics 5 (1), 2013

### **Experiments - Midge Swarms**

In the period June 2012 - May 2013, a new experimental campaign took place to collect new field data of swarming midges. The aim of the campaign was to collect perturbation/response data of swarms. In order to record the audio track, an omni-directional microphone has been used together with a digital audio recorder. An electronic circuit was developed to transform the manual trigger signal used to start the video acquisition into an audio tone, and feed it to the audio recorder. In this way, audio and video tracks were synced. Several acquisitions have been collected while perturbing the midge swarms with fixed-frequency acoustic pulses. The frequency range from 390 Hz to 480 Hz has been investigated, and tones have been played with durations equal to 0.25 s and 0.50 s. The most significant reaction of the swarm has been obtained with tones at 480 Hz and 0.5 s long. In most cases the typical reaction of a swarm to a sound input is revealed by a sudden expansion of the swarm. Swarm data under noise perturbations are currently under investigation.

## **Tracking**

Some modifications have been implemented in the tracking software in the period June 2012 - May 2013. The software has been used to process three more video acquisitions of flocking birds, and eleven video acquisitions of swarming midges. This work allowed us to find the optimal tuning of the tracking parameters for midge data. Large midge swarms have been processed, up to swarms of 700 individuals. The most successful tracking elaborations are summarized in Table 1 of Publication #2.

### **Publication #2**

## **Superfluid Information Transfer**

In the reporting period we made a significant discovery in collective decision-making. In biological systems, group decision-making requires a change of state of all individuals, with the risk of cohesion loss. Therefore, it is crucial to understand the main factors that affect the efficiency of information transport during collective changes of state.

By using the retrieved 3D trajectories of individual birds, we could quantitatively characterize the formation and propagation of turns across starling flocks. We discovered that the information to turn propagates linearly in time with negligible damping, in contrast with current theories of collective motion, which predict a diffusive and dissipative transport of directional information. We formulated a novel theory that recognizes the existence of a conserved spin current generated by the rotational symmetry of the system. Our theory predicts that the speed of propagation of information must be larger the stronger the flock's orientational order, which is quantitatively confirmed by the data. Surprisingly, our novel theory is mathematically equivalent to that of second sound propagation in superfluid liquid Helium, which is a compelling demonstration of the powerful consequences of symmetry in the laws regulating natural systems.

### **Publication #1**

## **Section 4 - Accomplishments during the fourth year of performance (2013-2014) of the group of Co-PI Cavagna in Rome**

In this reporting period we have: collected new experimental data of mosquito swarms in the laboratory; processed and analyzed a first part of the mosquito data; further analyzed the experimental data of midge swarms in the field collected during the previous years, and developed new theoretical approaches and numerical models of collective animal behavior; validated with synthetic data visual tracking software; wrote and submitted results in high profile peer-reviewed journals.

### **Publications**

- (1) A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, S. Melillo, L. Parisi, O. Pohl, B. Rossaro, E. Shen, E. Silvestri, and M. Viale, Collective behaviour without collective order in wild swarms of midges. Accepted for publication on PLOS Computational Biology (2014). Preprint arXiv:1307.5631 [cond-mat.stat-mech] (2014).
- (2) A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, T.S. Grigera, A. Jelic, S. Melillo, L. Parisi, O. Pohl, E. Shen, and M. Viale, Information transfer and behavioural inertia in starling flocks. Accepted for publication on Nature Physics (2014). Preprint arXiv:1303.7097 [cond-mat.stat-mech] (2013).
- (3) A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, A. Jelic, S. Melillo, L. Parisi, F. Pellaccini, E. Shen, E. Silvestri, M. Viale, Tracking in three dimensions via recursive multi-path branching. arXiv:1305.1495v2 [q-bio.QM] (2014). Manuscript submitted to Transaction of Pattern Analysis and Machine Intelligence.
- (4) A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, S. Melillo, L. Parisi, O. Pohl, B. Rossaro, E. Shen, E. Silvestri, and M. Viale, Finite-size scaling as a way to probe near-criticality in natural swarms. Submitted to Physical Review Letters (2014).
- (5) A. Cavagna, L. Del Castello, I. Giardina, T. Grigera, A. Jelic, S. Melillo, T. Mora, L. Parisi, E. Silvestri, M. Viale, A.M. Walczak, Flocking and turning: a new model for self-organized collective motion. Submitted to the Journal of Statistical Physics (2014). Preprint arXiv:1403.1202 [cond-mat.stat-mech] (2014).

### **Experiments - Mosquito Swarms**

In the period July 2013 – December 2013 a new experimental data-taking campaign took place to collect new 3d data of *Anopheles gambiae* mosquitoes swarming in a controlled artificial environment.

In collaboration with the Genomics, Genetics and Biology Pole at the University of Perugia, Italy, a new experiment was designed and set up. The pole offers unique facilities for mosquito population studies, including several large swarming cages (5x3x2.5 m, LxWxH) with computer-controlled temperature, humidity, illumination intensity and illumination frequency, as well as a large insectary for mosquito rearing. Using the proper temperature and humidity conditions,

together with the simulated daylight cycle, we were able to induce a fraction of the mosquitoes introduced inside the cage to swarm over an artificial landmark positioned on the ground. Swarms up to 200 individuals were formed and recorded. To the best of our knowledge, this is the first time that large mosquito swarms were formed in an artificial environment.

The video acquisition setup used for wild swarm of midges during the previous years was adapted to this specific indoor application (camera optics and supports). A powerful near-infrared (NIR) illumination system was designed, purchased, and installed in the cage: it provided the necessary illumination for video acquisitions, without disturbing with visible light the insects swarming at dusk. NIR-absorbant materials were tested and used as imaging background. The video system was calibrated using the same NIR light, and the 3d stereometric reconstruction was accurately tested.

Experiments were run on a daily basis during the artificial sunset phase lasting roughly 40 minutes. In total, 105 video acquisitions (16 s each) of mosquito swarming events were taken.

## **Data analysis - Mosquito Swarms**

In the period January 2014 – May 2014 a first part of the mosquito swarms data (roughly 20% of the acquisitions) was processed using our tracking software. Data analysis of the processed experimental events was started with particular emphasis on the connected velocity correlations, and on the order parameters. Mosquito data processing and analysis are ongoing.

## **Data analysis - Midge Swarms**

The most prominent trait of collective behavior is the emergence of collective order. Swarms of midges, though, are not collectively ordered. Moreover, swarms are generally found in proximity of a visual marker, such as a water puddle or a white feature over a black background. The presence of the landmark, together with the absence of collective order, makes the debate on whether swarms display truly collective behavior very intriguing.

In the reporting period, we analyzed 21 swarming events collected in the field. For each swarming event, we reconstructed the 3d trajectories of each midge using our tracking algorithm. We used these trajectories to retrieve position and velocity of each individual at each instant of time, and we investigated how much a change in the direction of one midge affects that of other individuals.

We discovered that, despite the lack of collective order, swarms exhibit non-trivial correlations of the direction of motion, totally incompatible with models on non-interacting particles. This proves that a true collective behavior emerges among midges while swarming, and that the true hallmark for collective behavior is not collective order but a strong and non-trivial correlation. We found that correlation increases sharply with the swarm density, indicating that the interaction between midges is based on a metric perception mechanism.

By means of numerical simulations we demonstrated that such growing correlation is typical of a system close to an ordering transition. Moreover, this indicates that midges adjust their mutual

distance according to the size of the swarm in order to be maximally correlated. As a consequence, the correlation length scales with the system' size and swarms exhibit a near-maximal degree of correlation at all sizes.

These results are summarized in two different papers, Publications #1 and #4.

## **Tracking**

In the reporting period, several sets of synthetic data were produced in order to validate the tracking algorithm and software. Computer simulations of bird flocks were run, and the simulated 3d trajectories were used to retrieve synthetic image data. The quality of the output trajectories was measured processing these datasets with known ground-truth, proving the excellent performances of the software.

These results were added to the first manuscript describing our tracking software, and the manuscript was fully rewritten. This version also benefits from the collaboration with a new author, Fabio Pellacini, professor of Computer Science. The new manuscript was submitted as Publication #3.